The
HOW
AND
WHY
Wonder Book of

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ATOMIC ENERGY

How and Why Wonder Books

An Atomic "Swimming Pool" Reactor

THE HOW AND WHY WONDER BOOK OF

ATOMIC ENERGY

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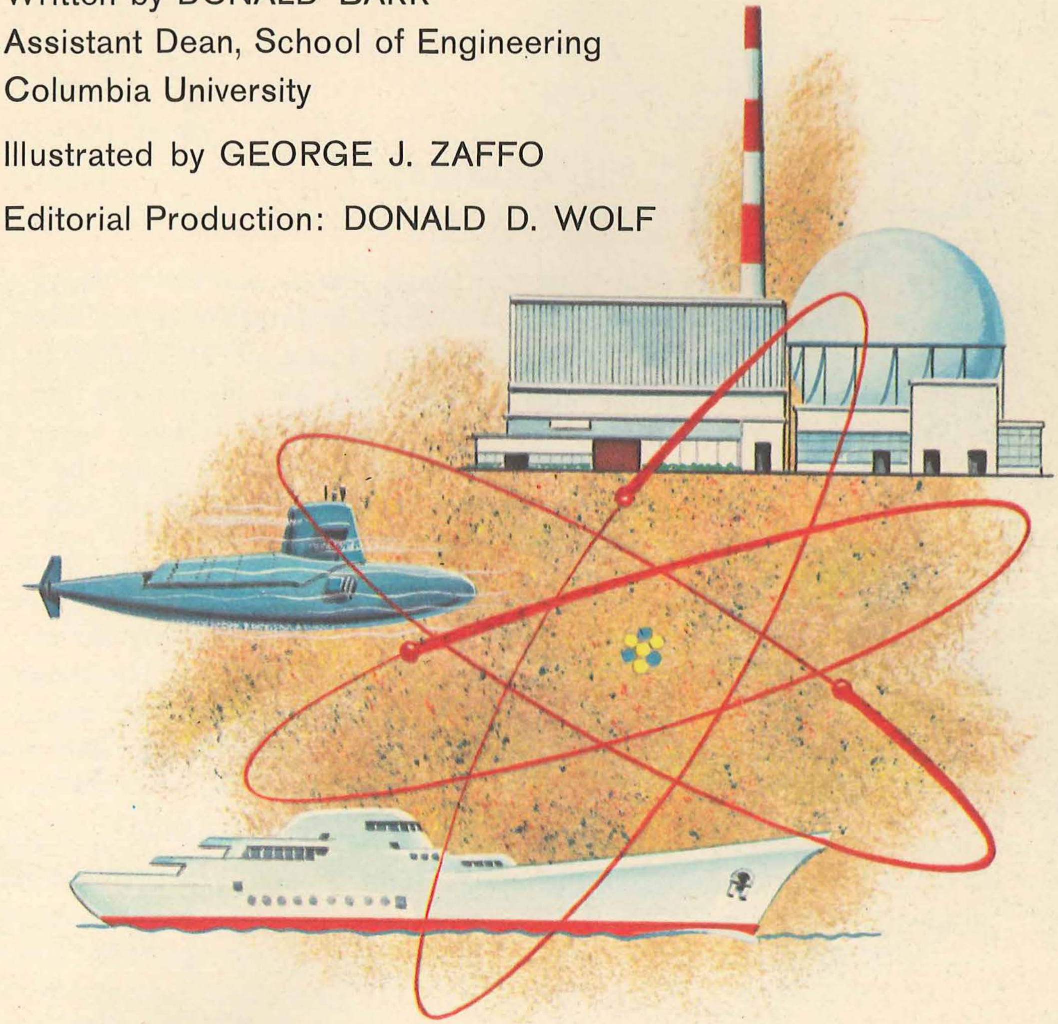

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WONDER BOOKS • NEW YORK

Introduction

Big ideas sometimes deal with very small things, and small things are often exceedingly important. Witness the atom. Scientists have had some of their biggest ideas about these tiny particles of matter. Their ideas about atoms have changed as discoveries have brought new information into the picture. *The How and Why Wonder Book of Atomic Energy* takes the science-minded reader along the exciting road of discovery about the atom that led to the first use of atomic energy in a controlled way, and tells how people from many countries made scientific contributions.

The life-blood of scientific activity is in exploring all parts of the universe — even the tiny parts represented by atoms — and explaining the events that take place. Though individual atoms cannot be seen, they are the basis of all matter. And in the search for more information about atoms, scientists gradually came upon new knowledge about the energy within. This book tells this wonderful story.

Parents and schools will want to place *The How and Why Wonder Book of Atomic Energy* alongside the other books in this series. It not only brings the young reader up to date on the development of atomic energy, but challenges one to think about the yet-to-come atomic age of the future.

Paul E. Blackwood

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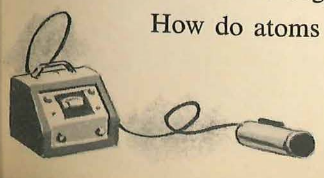
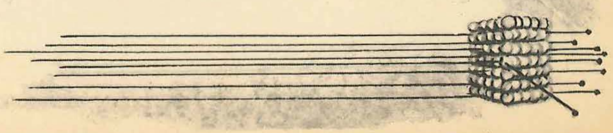
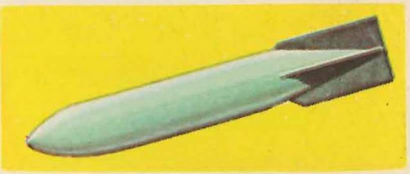
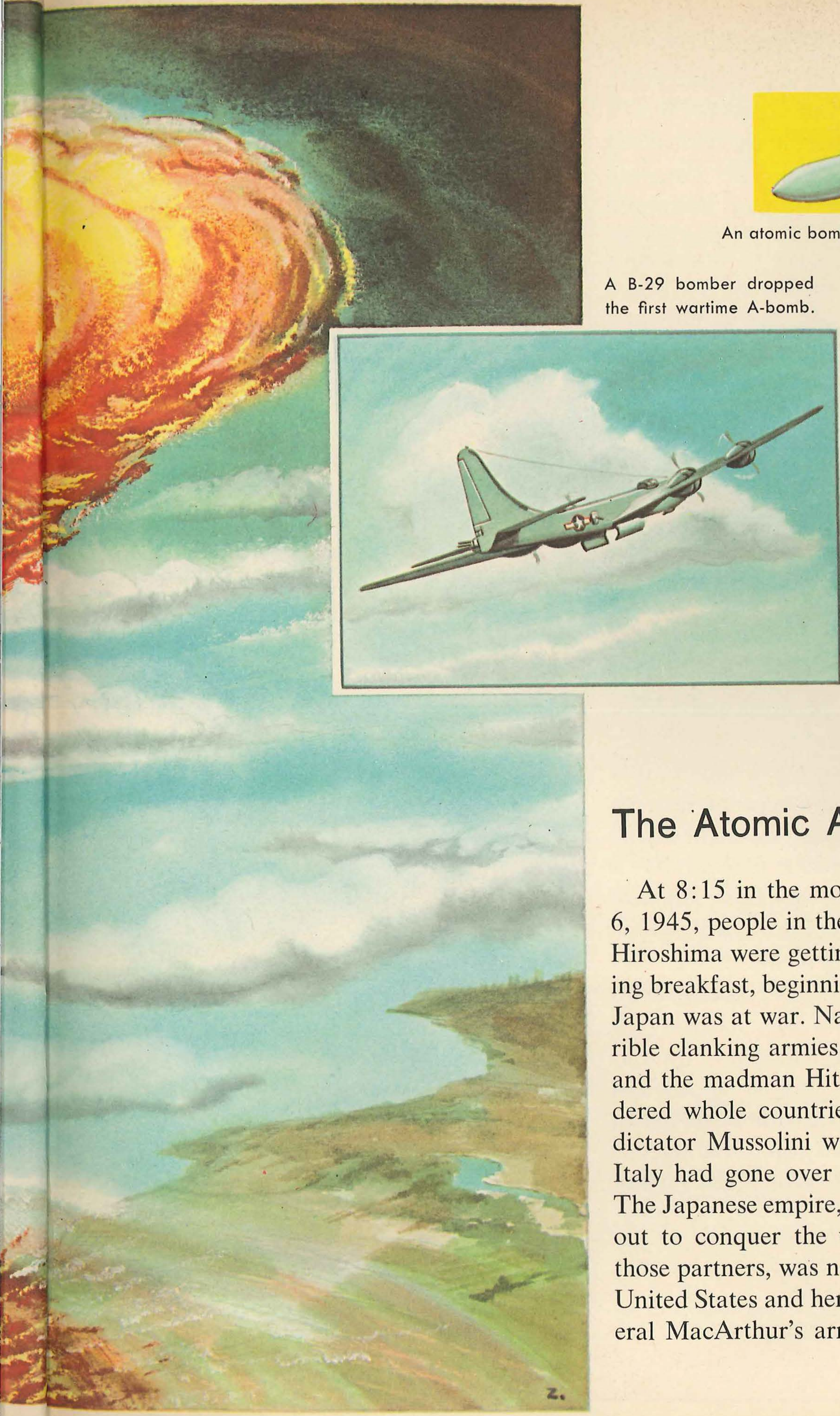






An atomic bomb destroyed Hiroshima.

A B-29 bomber dropped the first wartime A-bomb.



The Atomic Age Begins

At 8:15 in the morning, on August 6, 1945, people in the Japanese city of Hiroshima were getting out of bed, eating breakfast, beginning the day's work. Japan was at war. Nazi Germany's terrible clanking armies had been beaten, and the madman Hitler who had murdered whole countries was dead. The dictator Mussolini was dead, too, and Italy had gone over to the other side. The Japanese empire, which had started out to conquer the whole world with those partners, was now left to face the United States and her allies alone. General MacArthur's armies were already shooting and slashing their way into the islands that guarded Japan. For weeks American planes had rained fire bombs on Japanese cities. Thus far, Hiroshima had been spared. Then a lone American plane streaked over the city. It dropped one bomb. The Atomic Age had begun.

DEATH OF A CITY

There was a vast flash of fire, brighter than the sun, and hotter. There was a great shuddering of the earth and a great roar and a scorching wind. There was a cloud shaped like a huge mushroom, silently standing above the ruins. There was nothing left of the center of Hiroshima except charred, dusty rubbish from which deadly invisible rays were streaming. There were 78,150 people known to be dead and 13,983 people missing. From one bomb!

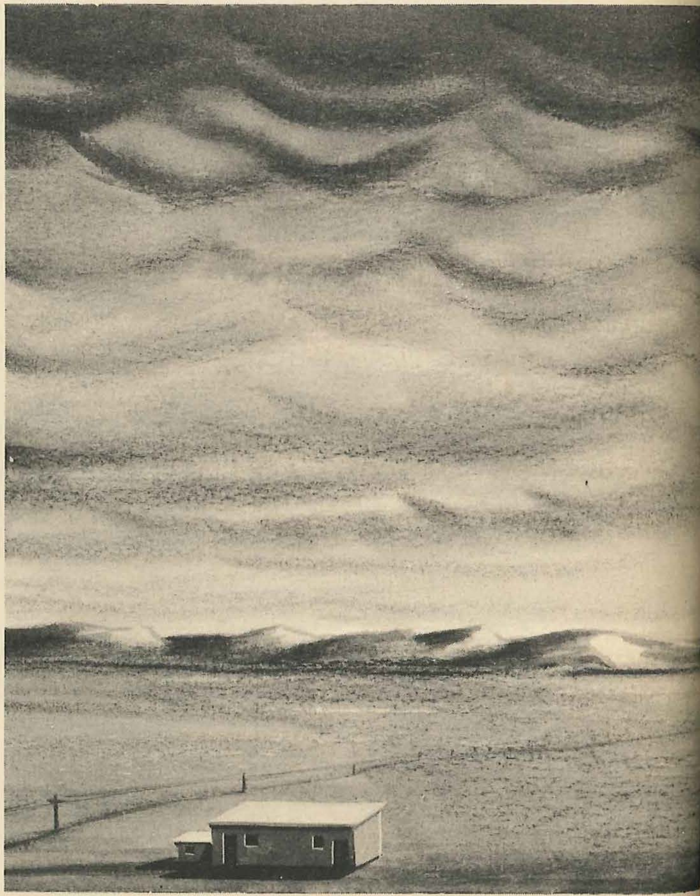
The President of the United States, Harry S. Truman, broadcast a warning to Japan. This, he said, was a new kind of bomb, a bomb which used the forces that made the sun hot, and America had more of these bombs. The President was slightly wrong in his science. But that did not matter. The Japanese knew that there *was* a new force in the world, and soon they surrendered.

On that August day, in laboratories all over the United States, scientists shivered and looked grim. That was not the way they had wanted the Atomic Age to begin.

Dawn in the Desert

Let us go back three weeks. It is a little before 3:00 o'clock in the morning on July 16, 1945. The rain is pouring down and the lightning is wildly stabbing the clouds over a lonely corner of Alamogordo Air Base in the New Mexico desert. It is not deserted tonight.

Men are scurrying through the darkness. There are soldiers, some of them wearing generals' stars. There are quiet men in business suits, whom the others address respectfully as "Professor." Between the crashes of thunder, they talk in little groups nervously. They go into a shed to examine some wires and instruments and drive away. Some go to another blockhouse a few miles away. Some drive six miles through the storm

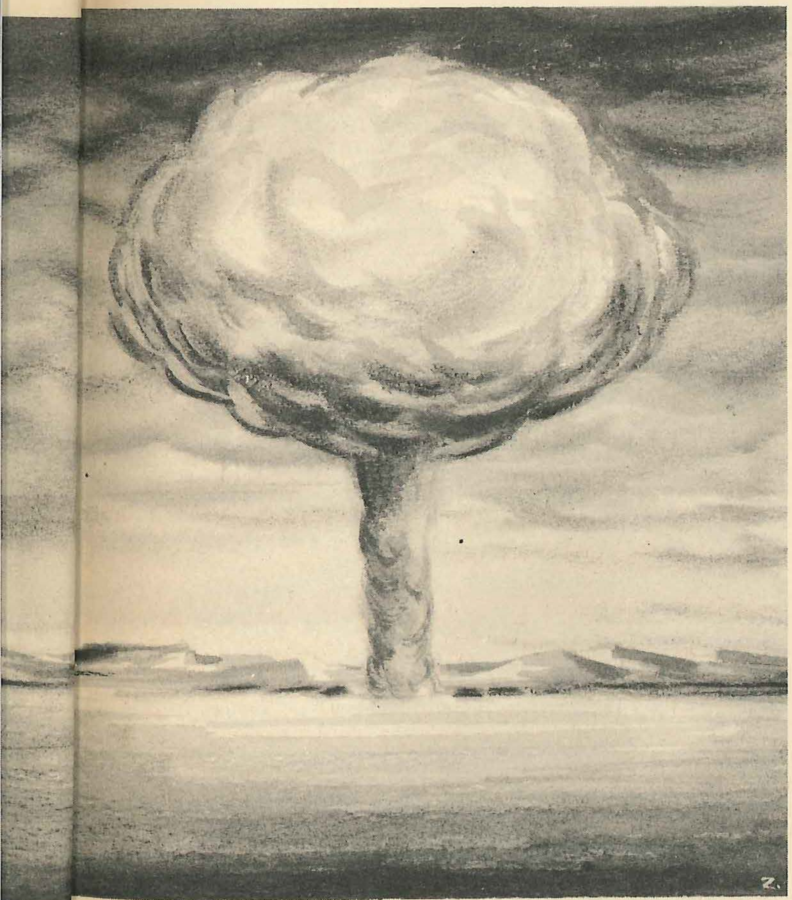


The first atomic explosion on earth occurred in the New Mexico desert near Alamogordo in July, 1945.

and climb a tall steel tower to peer at a bulky, strange device nestling there among more wires and instruments. This is the device which is to be tested — an atomic device. It is known simply as "Fat Man." The men keep looking at the sky.

ZERO HOUR

At 3:30 there is a decision. Fat Man will be tested. At 4:00 o'clock the rain stops, but the clouds are thick overhead. By 5:10, the men have all gathered in the blockhouses. A voice crackles from the loudspeakers: "Zero minus twenty minutes." Men are rubbing suntan lotion on their faces and arms. The talking dies down. Some of the men are praying. In one shed, when zero minus two is called, everyone lies on the floor, face down, with his feet pointing to the tower several miles away. In the other shed, the civilian scientist in charge of the project, Dr. J. Robert Oppenheimer, is hardly breathing. He holds onto a post to steady himself. At zero minus forty-five seconds, the automatic timers click on. The red hand glides around the clock face. Then the announcer yells, "Now!"



A blazing flash from the tower lights up the face of the desert and the mountains around it. There is an earsplitting roar which goes on and on. A blast of air knocks down two men who have stayed outside one of the sheds. An enormous, many-colored cloud boils up and up until it is eight miles tall. As it rises, the storm-clouds seem to move aside for it.

In the two sheds, the stiff faces have eased into smiles. Everyone is shaking everyone else's hand. There are shouts of laughter. A distinguished chemistry professor from Massachusetts throws his arms around Dr. Oppenheimer. "We did it! We did it!"

Fat Man has passed the test. The first atomic explosion on earth has just taken place.

A Dangerous Game

Let us go back two and a half years. It is mid-morning in Chicago, December 2, 1942. For a long time the University of Chicago has not played any football in its stadium, Stagg Field. It is a pity to waste the place. Under the grandstands there are rooms and courts for playing other games, and something is certainly going on in a squash court under the West Stands. But this is not squash, which is played with a rubber ball and rackets. This game is played with balls and rackets too small to see — hundreds of millions of them. The players can get hurt.

Above one end of the court is a balcony. Toward the other end, there is a monstrous black pile of something. It is strange-looking stuff, yet it somehow seems familiar. It is not metal, yet it is shiny, even a little greasy-looking. Where have we seen it before? In a pencil.

The "lead" in a pencil is not lead at all, but a form of carbon called *graphite*. Carbon comes in many forms, including coal and diamonds, but graphite is best for playing the atomic game. It can be sawed into neat shapes like wood. It can be made very pure. It is not rare.

FIFTY-TWO TONS OF URANIUM

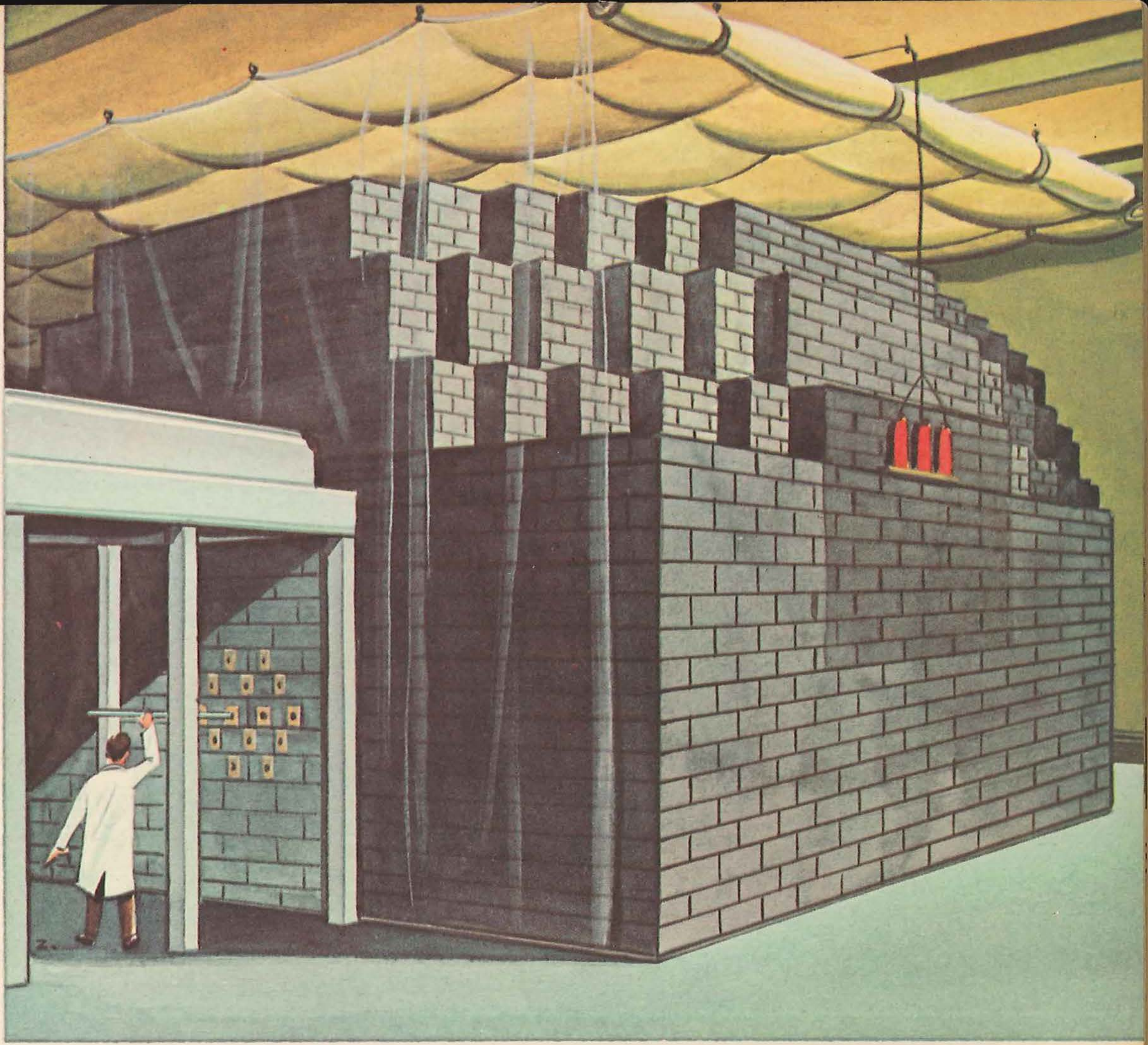
This pile is made of neatly sawed bricks, stacked crisscross. It is very pure — or the players in the squash court hope it is — because if it isn't, something might go terribly wrong. And there are 1,350 tons of graphite in the court, piled 30 feet wide, 32 feet long, 21½ feet high. Some of the bricks in the middle of the stack have holes drilled in them. In these holes are lumps of a strange, rare metal called *uranium*. Almost all the uranium metal in the United States of America — fifty-two tons of it — is here, buried in the big black pile under the seats at the football field. Also buried in the pile are 14,500 lumps of other stuff that has uranium in it.

Other holes have been drilled through the stacked graphite bricks. Lying in these are long rods of another rare metal, called *cadmium*. What the strange uranium can do, the strange cadmium can stop — the players hope.

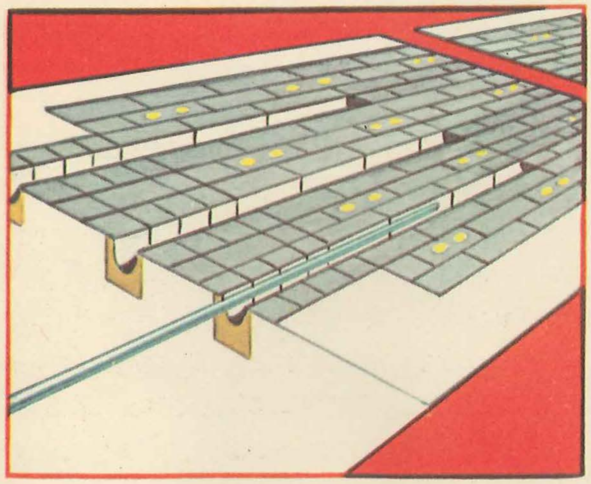
For this game has never been played before, not since the creation of the earth. As the cadmium rods are pulled out of the pile, millions of tiny "balls" — much too small to see, even with a microscope — will shoot out of the uranium lumps. They will go right through the graphite and hit nearby uranium lumps, knocking more tiny balls out of them. These, too, will begin flying around and knocking more balls into the game. And the uranium and graphite will get hotter and hotter and hotter, like a furnace.

WILL IT WORK?

Now if the players are wrong, either of two things might happen. One is — nothing. There may not be enough balls, or they may not shoot through the graphite. Three years of hard work and millions and millions of dollars would be wasted. The other thing that might happen is — an explosion. There may be too many balls. The "furnace" may get too hot. And if it does, it could blow up not only the players and the squash court and the football field, but Chicago, Illinois.



The first atomic reactor, at Stagg Field in Chicago, Illinois, was a huge stack of carbon bricks. The central bricks had holes with lumps of uranium in them. Other holes were drilled through the stack for the cadmium "control rods," shown in diagram below.



Now the players are ready. The captain of the team is an Italian-born scientist named Enrico Fermi. He invented the game. He has come from Columbia University in New York, a thousand miles away, to play. One of the players has his hand on a cadmium rod, waiting for the captain's signal to start the game. Three players are standing on top of the pile with big pails of water in their hands. The water has cadmium in it. If the game gets too "hot," they will douse it with the cadmium water before it blows up — *if* they have time. The scorekeeper is sitting at a cabinet covered with dials, like the dashboard of a car multiplied by ten. The dials tell him how many balls are flying, how hot the pile is getting. He will try to cry out a warning if the game goes wrong.

Fermi is sure it will not go wrong, and he is a world-famous physicist. He has checked his plans and calculations over and over again. He has checked them this morning. He does not think he will be like Mrs. Murphy's cow, which kicked over a lantern and started the Great Chicago Fire.

THE GAME STARTS

He gives the signal. A cadmium rod is pulled out. Another. All but one. The scorekeeper reports that the game is under way inside the great black heap.

The player takes the last cadmium rod and slowly pulls it out one foot. The scorekeeper's instruments click out the news — the pile is warming. It steadies, as Fermi's calculations said it would, before it gets really hot. The player pulls the rod out a little more. Then a pause. Check the instruments. Check the calculations. A little more. Check. A little more. Inch by inch.

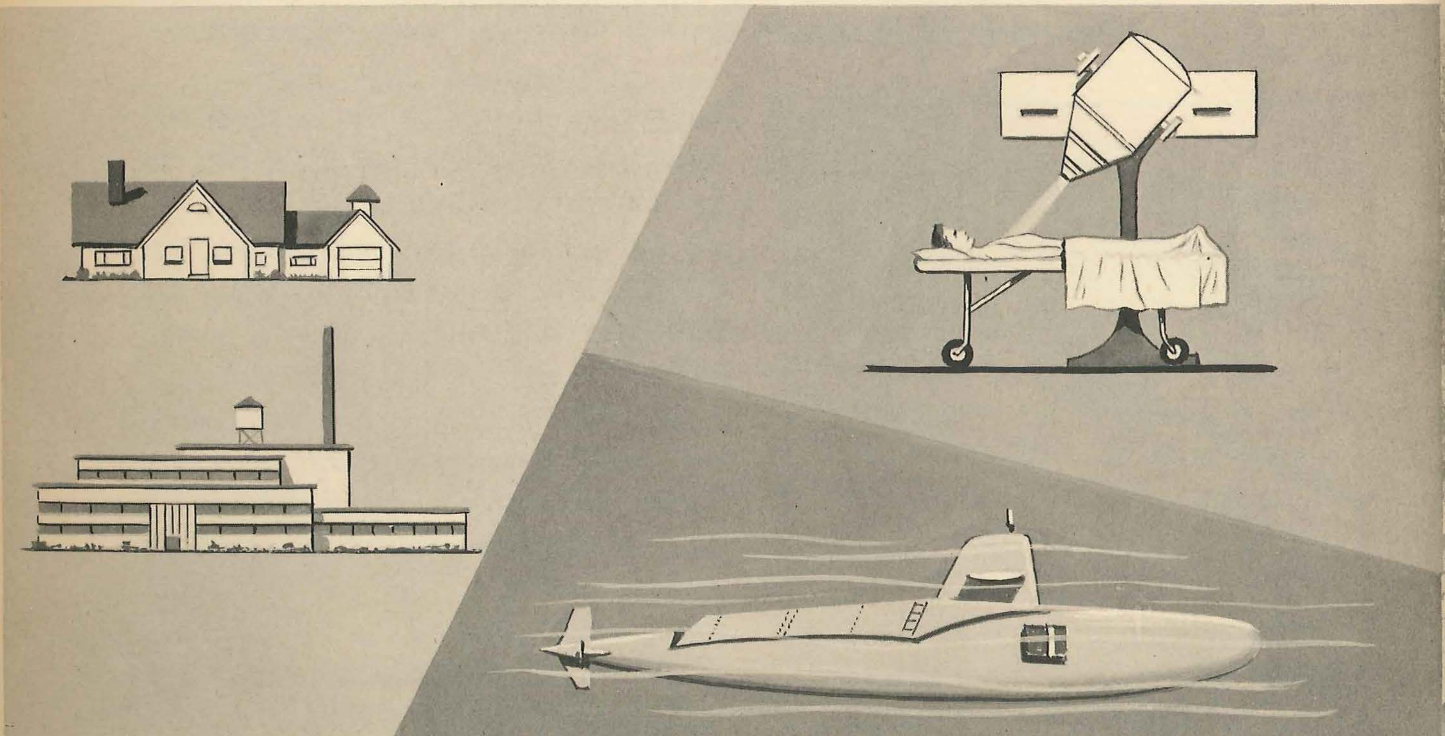
It is lunchtime. Professor Fermi and his team go out to eat. After lunch, they inch the last cadmium rod out of the pile. At 3:25 P.M. the instruments have news. The pile has "gone critical" — it is hot — it is working.

Will it go too far, get too hot, explode? The clocks tick away the minutes. Still safe. At 3:53 P.M., Fermi tells the player with the rods to put them back. The game is over.

It is won. Man has built an atomic furnace. It can make electricity to light houses and run factories. It can make medicine to cure diseases. And it can make terrible explosives capable of killing thousands of people in a second.

One of the players reaches into his

Science has learned to use the energy of the atom for homes, factories, submarines, surface ships and medicine.



luggage and pulls out a bottle of Italian red wine. Fermi sends for paper cups. The members of the team hold their cups up — "Here's to the Atomic Age!"

A Little Extra Work

Let us go back four years. It is the evening of January 25, 1939, a cold, blowy evening in New York City. In a small, messy room in a basement at Columbia University, three men are working late.

For young Professor Dunning, it has been a busy day, and there is a lot more to do. He had lunch today with his friend Professor Fermi, who told him some exciting news. The news came in a roundabout way, from Berlin, Germany.

Atomic power can also be used destructively.

Things are bad in Berlin. The madman Hitler is running Germany and Austria, and he is having thousands of people beaten or shot because he doesn't like their religion or their political beliefs or because they oppose the inhuman methods of the Nazis. Many Germans and Austrians are escaping to other countries. One Austrian woman, Dr. Lise Meitner, who is now in Denmark, is an important physicist.

LETTER FROM BERLIN

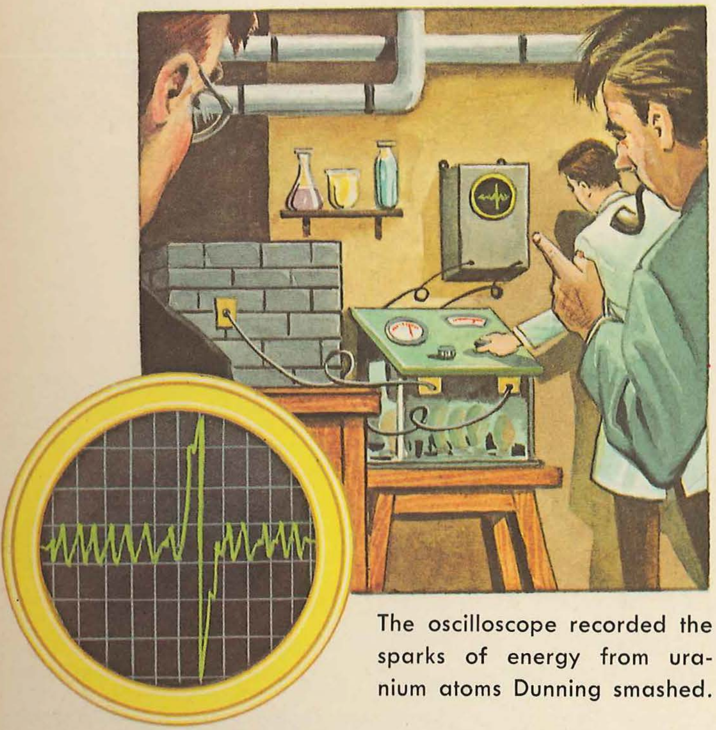
A few weeks ago she got a letter from Otto Hahn, a chemist who has stayed in Germany. He said he had been experimenting with some uranium and discovered a strange thing — some of it had turned into another metal entirely. He hardly dared think what that meant. As soon as she read this, Dr. Meitner saw what it meant. She talked it over with friends in Denmark. One was Niels Bohr, who is the world's greatest expert on atoms. And Bohr was just leaving for a visit to America.

A few days ago he arrived and told some American scientists he was going to give a report on this new discovery to a meeting in Washington, tomorrow, January 26. The news has been spreading fast. Fermi talked it over with Dunning at lunch today, and then left for Washington to attend the meeting.

Young John Dunning, too, sees what it means. He sees that if you really do to uranium what Otto Hahn says he did to uranium, little bits of stuff will shoot out of it — little balls too small to see, even with a microscope. And there will be sparks or flashes of energy — too small to see or feel. So all afternoon he has been trying to get equipment set up for a wonderful experiment. He is going to do what the German chemist did, and he is going to prove that the little bits of stuff really do fly off, and he is going to measure the energy. . . .

A SOUND NOBODY EVER HEARD

Dunning has clever hands. He has a way with gadgets. Here are some chunks of lead like children's blocks, and some chemicals and pipe and a lot of wire and some radio tubes and a small metal case with a round glass screen in one end. This is the equipment. It looks pretty sloppy, but it will work. It will do three things. It will change the uranium. It will detect any flying bits of stuff or sparks of energy. And each time anything is detected, it will send an electric current into the thing that looks like a toy television set.



The oscilloscope recorded the sparks of energy from uranium atoms Dunning smashed.

Two scientists who are working with him have come. Everything is ready. Dunning turns a switch on the case with the window. A glowing green line appears across it. He switches on the rest of the equipment. The green line becomes wiggly, almost furry. And then it happens.

A long green streak shoots up from the furry line. Blip! The signal. A second later, another. Blip! Blip-blip! Blip! Blip-blip-blip . . .

The three men are looking at atomic energy.

A Very Strange Idea

What is the universe made of?

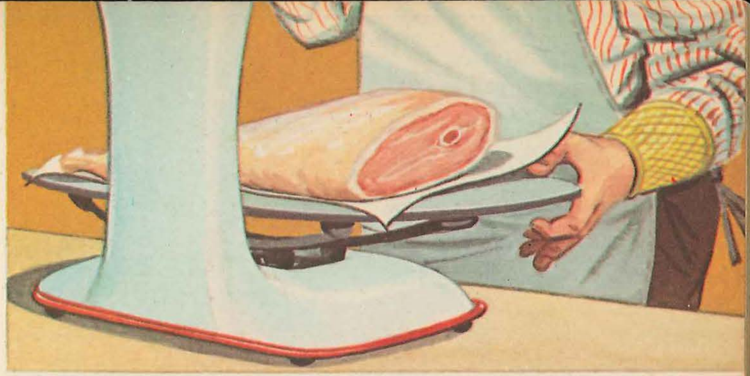
The whole universe — the great flaming stars scattered over billions of billions of miles, the earth under our feet, the air we breathe, the light we see by, the mysterious tiny blood cells flowing through our veins — all of this is made of only two kinds of things. One is *matter*. The other is *energy*.

Intelligent men have been living on the earth for 100,000 years. But it is only sixty years ago that they began to find out what matter and energy really are. We still have a great deal to learn.

Have you ever had this experience? You stare at a word on a page, an ordinary word you have read hundreds of times, and after you concentrate on it for a few minutes it begins to look a little bit "wrong." The longer you study the letters in it, the stranger it becomes, until you almost believe it is misspelled. (Try it for three minutes with the word ENERGY. . . . Now: is that a real word?) It is the same way with the science of physics. As we study the whole page of the universe, the complicated things become wonderfully simple. But when we concentrate on the simple words on the page of the universe, they become very complicated and unfamiliar.

What is the difference between matter and energy?

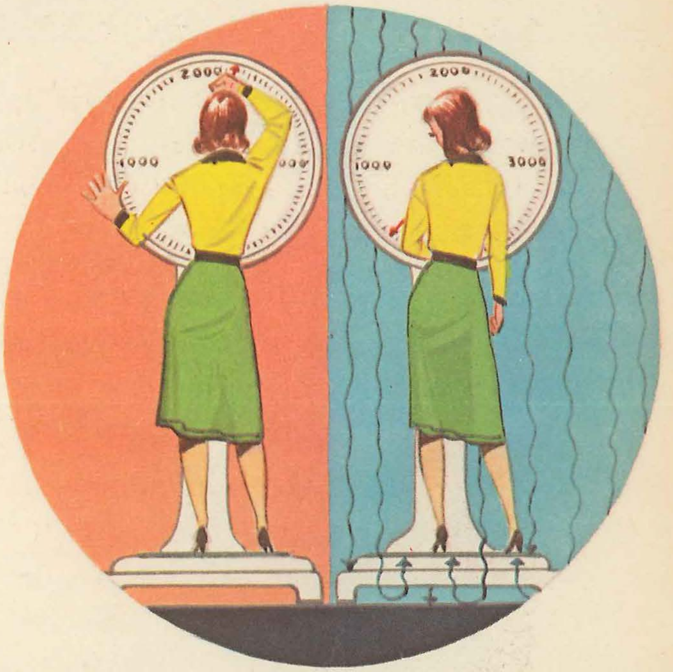
At first glance it looks as if matter and energy are quite different — matter weighs something and energy does not. However, since the year 1900, physicists have been giving this question a second, third and fourth glance. They have been puzzled by the fact that energy often acts like matter and matter acts like energy.



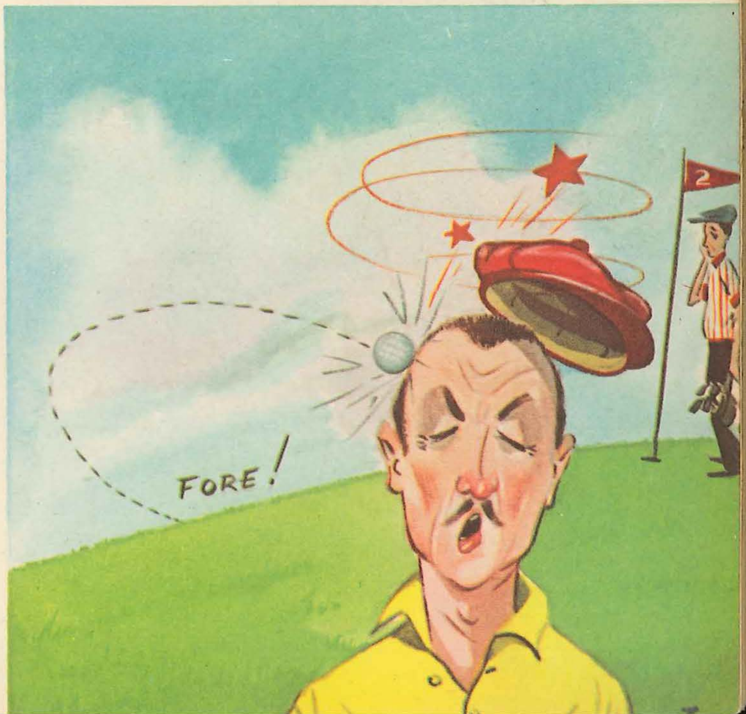
Mass is the amount of matter in a thing — meat, for example. One way to measure mass is with a scale.

But that's not always easy. The air above this scale has one ton of mass. Why doesn't what you see here take place?

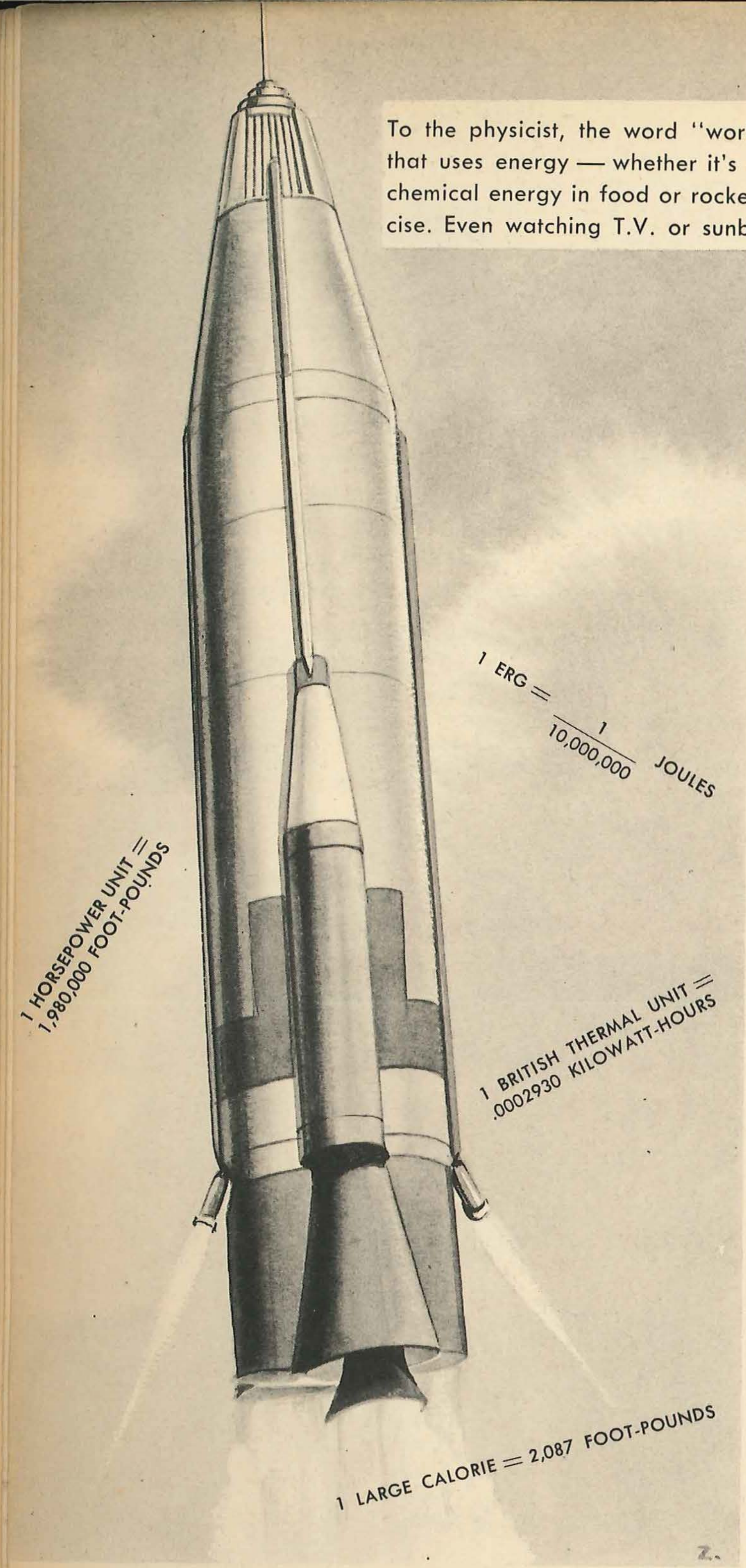
Answer: Because the air also gets underneath the scale and pushes upward, just like water under a rowboat.

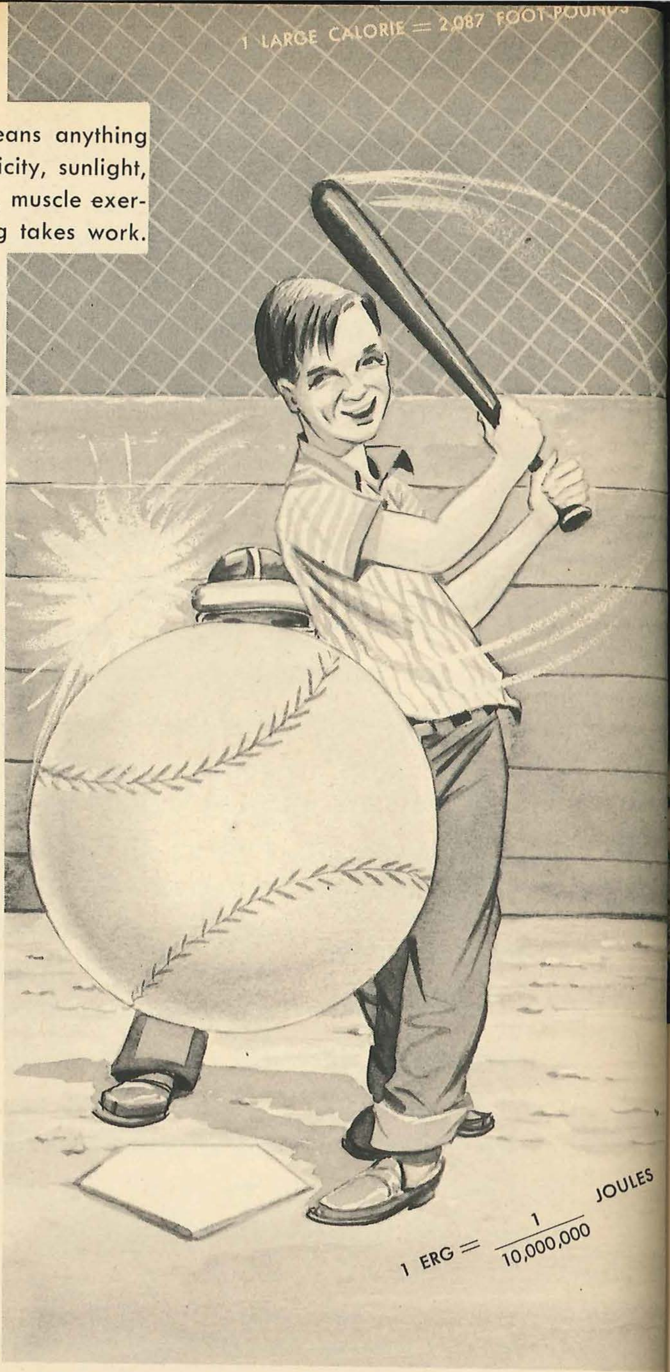


Another way to measure the mass of a thing is by the kind of wallop it gives when it hits you head-on.



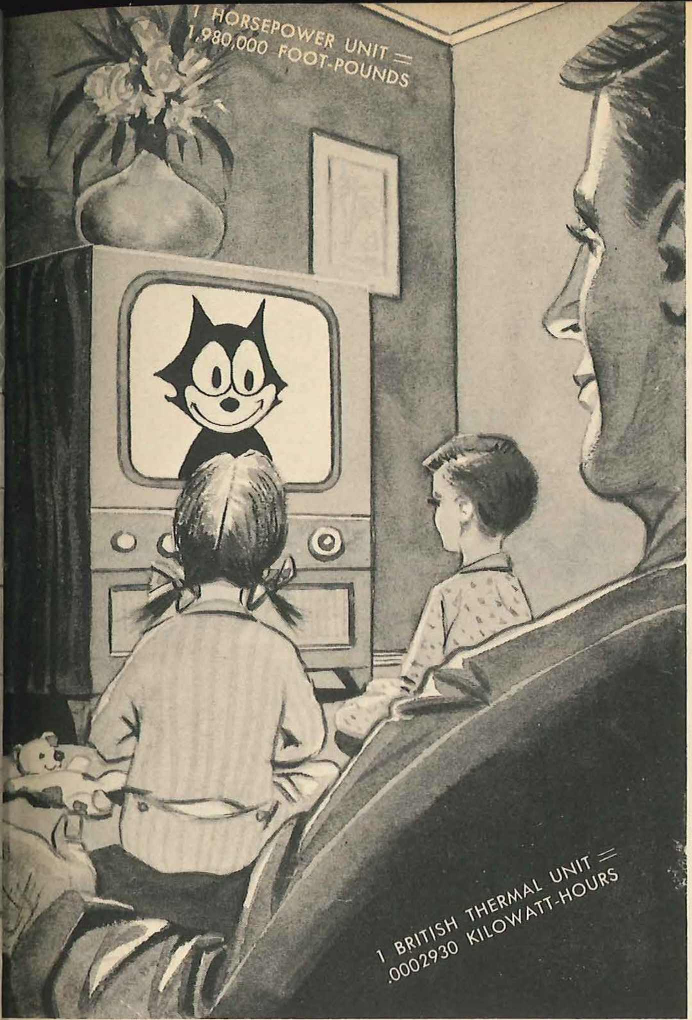
To the physicist, the word "work" means anything that uses energy — whether it's electricity, sunlight, chemical energy in food or rocket fuel, muscle exercise. Even watching T.V. or sunbathing takes work.





The paper this book is printed on is matter, and it seems fairly solid and not particularly strange. It weighs something in your hand. Blow against it. It moves a little. Blow harder. It moves more. It has what physicists call *mass*.

The breath you blow against the book is not solid like the book, and at the moment you cannot tell that it weighs anything. There are several hundred miles of air piled on top of you, and yet you are not crushed. But a second's thought tells you that, although the matter in your breath is much more loosely arranged than the matter in the book, it has body to it, for when you blow up a balloon, you can feel the air



inside. And air actually weighs quite a lot. For a blimp, carrying crew and engines and fuel, floats in the sky by weighing a little less than air, just as a submarine floats in the sea by weighing a little less than water. So even very thinned-out matter has mass.

How can we tell matter from energy?

But the light by which you are reading this book is something else. It does not seem to weigh anything. You can shine a flashlight beam into a balloon and the balloon will not fill. If you blow sideways against the beam, it will not shift. Light does not seem to have any mass. It is not thinned-out matter, but energy.

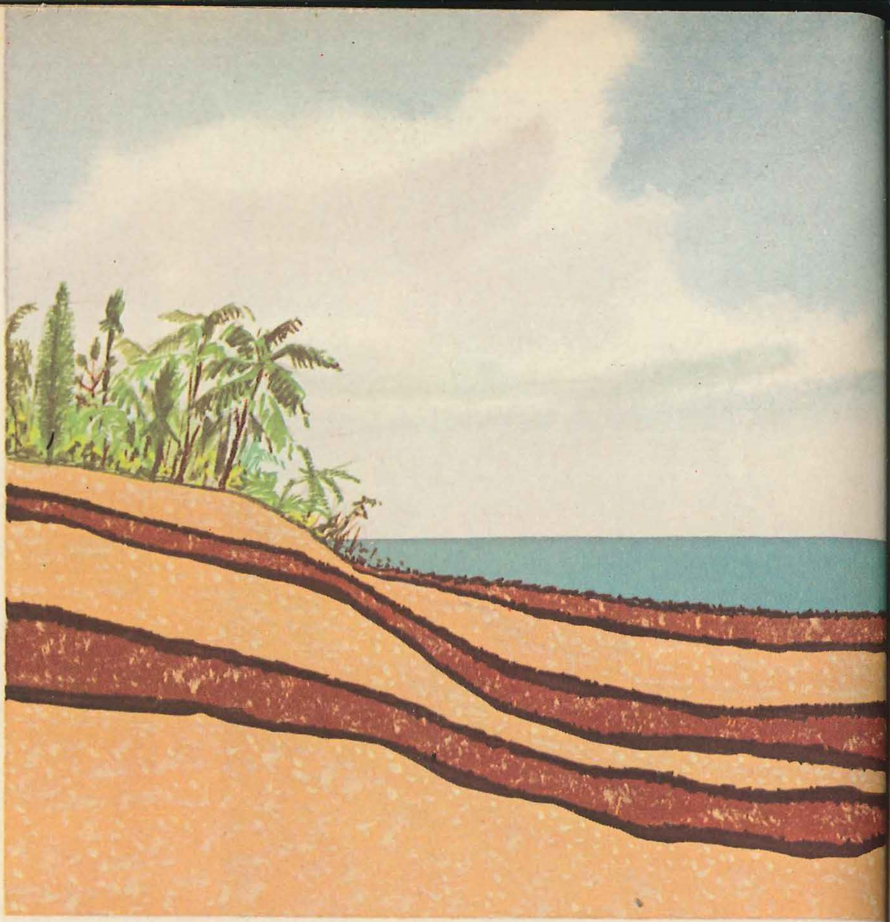
Yet, when we stare at matter very hard and long, using the marvelous electronic and magnetic eyes that science has invented, it begins to look very strange. It does look almost like a queer kind of thickened-up or frozen energy.

What is energy?

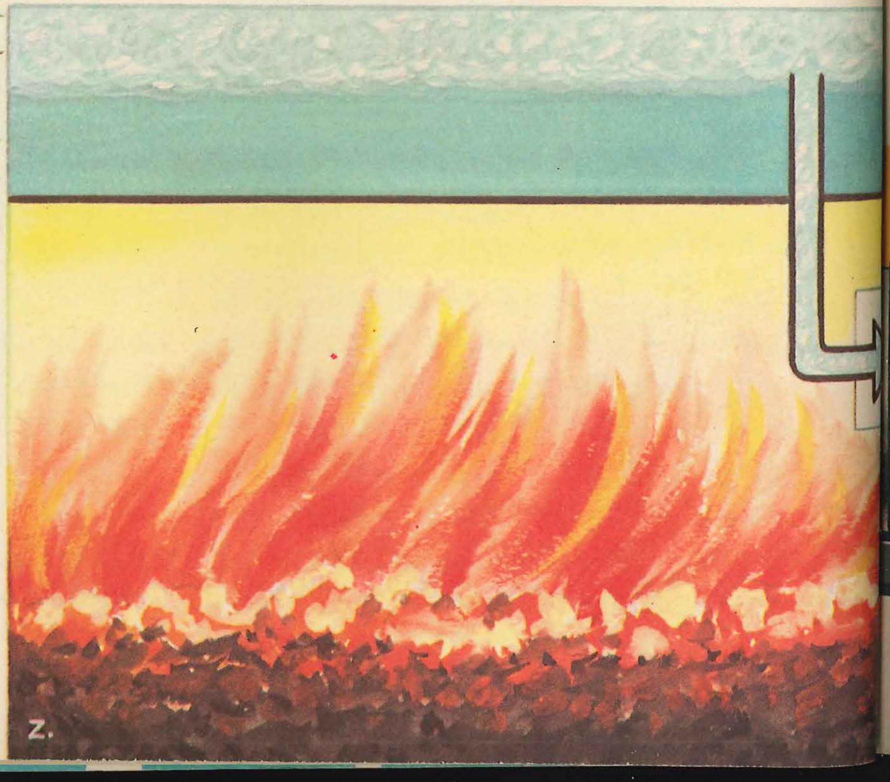
We still do not know very clearly what energy is. But we know what it does. It does *work*. Technically, we say that work is the applying of a force over a distance. More simply, it is the use of energy to move things or to change things. Work may be moving pieces of matter around — lifting a girder up the skeleton of a skyscraper, drilling a hole in the earth, hammering a nail, weaving cloth. Work may be changing the insides of matter — refining iron ore into iron metal, changing iron to steel in an open-hearth furnace, using derivatives of coal, air and water to make material called nylon. Work may be magnetizing and demagnetizing something, as happens thou-

Energy is stored in matter. Coal is black and cold, but it stores light and heat from the sunlight of over three hundred million years ago.

Prehistoric ferns grew in large numbers, using the sunlight to build up plant fibers from the simple chemicals of the air and water.



Drowned in swamps and shifting oceans, crushed under huge layers of rock, the leaves and stems of the plants turned hard and black, but they did not change back to the original chemicals.



When you burn coal, the fossils of plants turn back to chemicals, something like the ones from which they were made, and the ancient sunlight is released — as fire.

sands of times a second in a loudspeaker. Work may be changing the temperature of something.

How do we measure energy?

We measure energy by the amount of work it does. We measure it in *foot-pounds.* For example, 20 foot-pounds is the amount of energy it would take to lift 2 pounds 10 feet, or 10 pounds 2 feet, or 5 pounds 4 feet. We also measure energy in *calories.* A "small calorie," the kind people count when they are dieting, is a thousand times bigger — so a man on a strict diet might eat only enough food to give him 3,000,000 foot-pounds of energy a day. We also measure energy in *joules, ergs, horsepower-hours, kilowatt-hours,* and all sorts of units, depending on the kind of work we mean.

Can we "make" energy?

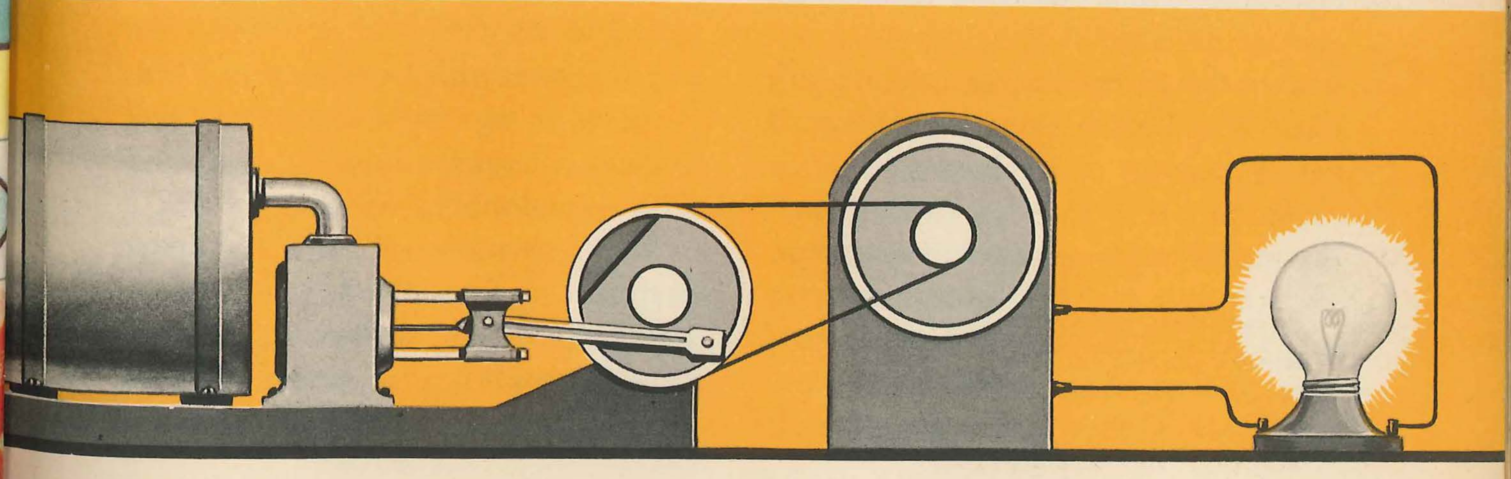
In the year 1900, every physicist in the world would have told you that we cannot make new energy — we can only use energy which exists already. Of course we can make electrical energy, but we make it out of other energy, energy in another form.

Energy exists in many forms, and we have learned how to change it from form to form. Suppose you build a fire. It gives you *heat-energy.* With that you could boil water and use the steam to push the piston of the steam engine, which would turn a wheel, giving you *mechanical energy.* That might in turn drive a dynamo, changing the mechanical energy into *electrical energy.* That electricity could work a lamp, which would turn it into *light-energy.* Or a stove, which would change it back to heat-energy. Or a motor, which would change it back to mechanical energy.

In doing all this, said the scientists of 1900, you have not added any energy to the universe. You took some energy which had been stored up in matter — just as mechanical energy is stored in a wound-up watchspring — and *converted* that energy until it had done the work you wanted.

They were nearly right, which in science, where there is no "nearly," means that they were wrong.

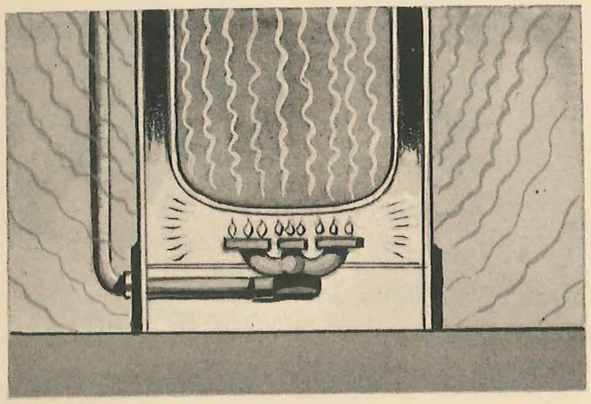
Energy can be changed to other forms. Fire (heat energy) boils water. Steam drives an engine which turns a wheel (mechanical energy), which drives a dynamo (electrical energy), which lights a lamp (light energy).



The scientists of 1900 were also sure we could never destroy any energy. We could only lose it.

Do we burn up energy?

Energy is always leaking away and taking forms in which we cannot catch it and use it. The fire under your boiler heats other things besides the water in the boiler. The steam seeps out around the piston. The air around the hot cylinder of the steam engine warms up and blows away. The dynamo heats up from friction, and this energy is also carried away by the air. Your electric wires get warm. The light bulb gives off heat as well as light, and that, too, is carried away. So as you go on converting energy from one form to another, you are, so to speak, cooking the wind. At last, this escaped energy radiates off, like the sun's rays, into the endless cold of outer space.



Fire under a boiler heats other things besides water.

Where does used energy go to?

But it still exists somewhere out there. It is not destroyed. The human race sends about 90,000,000,000,000,000,000 foot-pounds of energy out into space each year. So in 1900, physicists had the idea that we can never change the amount of energy in the universe, and they were so sure of this that they called it a scientific law — the *Law of the Conservation of Energy*. Now we know it is only half a law.

What happens when we burn matter?

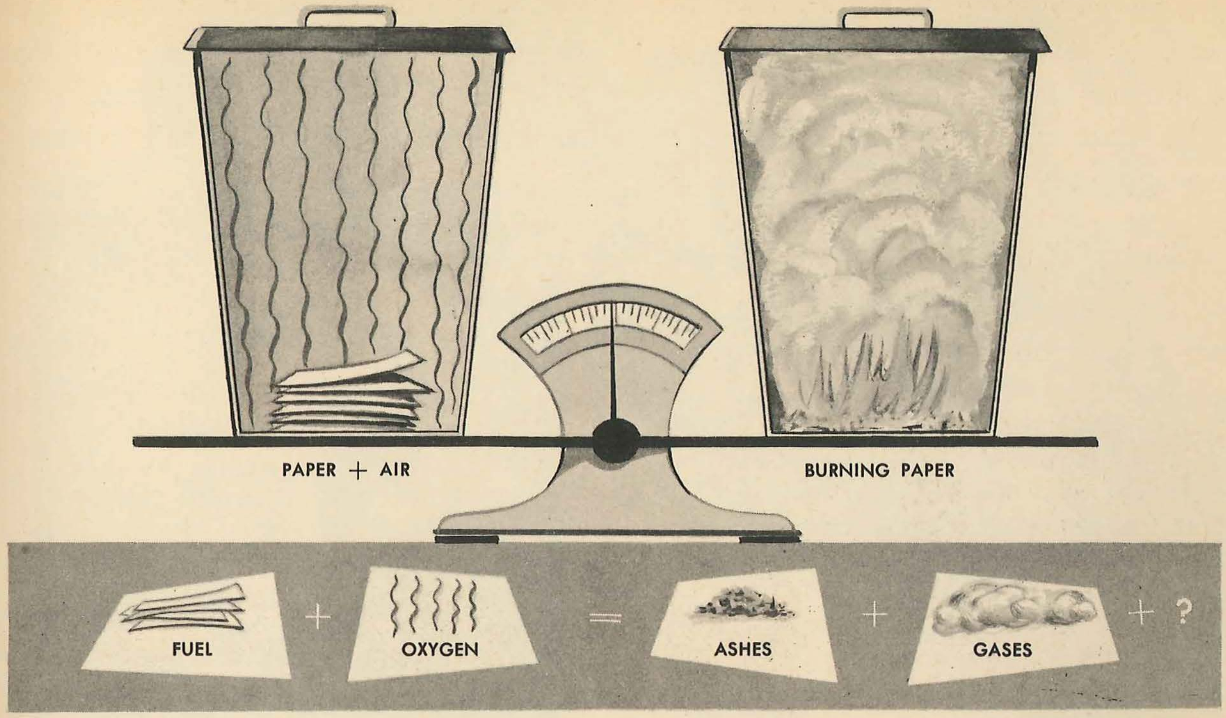
Suppose you were to hold a lighted match to the corner of a stack of paper. The paper would catch fire and the bright hot flames would eat across the sheets until the paper was burned up Some heat-energy and some light-energy would be given off, while one half an ounce of solid matter would seem to vanish. A bit of fluffy ash and a floating cloud of smoke would apparently be all that was left.

Wouldn't you have changed that matter into energy then? Doesn't that mean matter and energy are really forms of the same thing after all?

Can we change matter into energy?

In 1900, you could not have found a single physicist who would have answered "yes" to those questions. Now you could not find a physicist who would answer with a straight "no." This is the most important change of mind in human history. It is changing our lives — and maybe our deaths.

So we should think carefully about such an experiment with a stack of paper. To burn it scientifically you would have to burn it inside a can. You would have to use a big can, so as to hold all

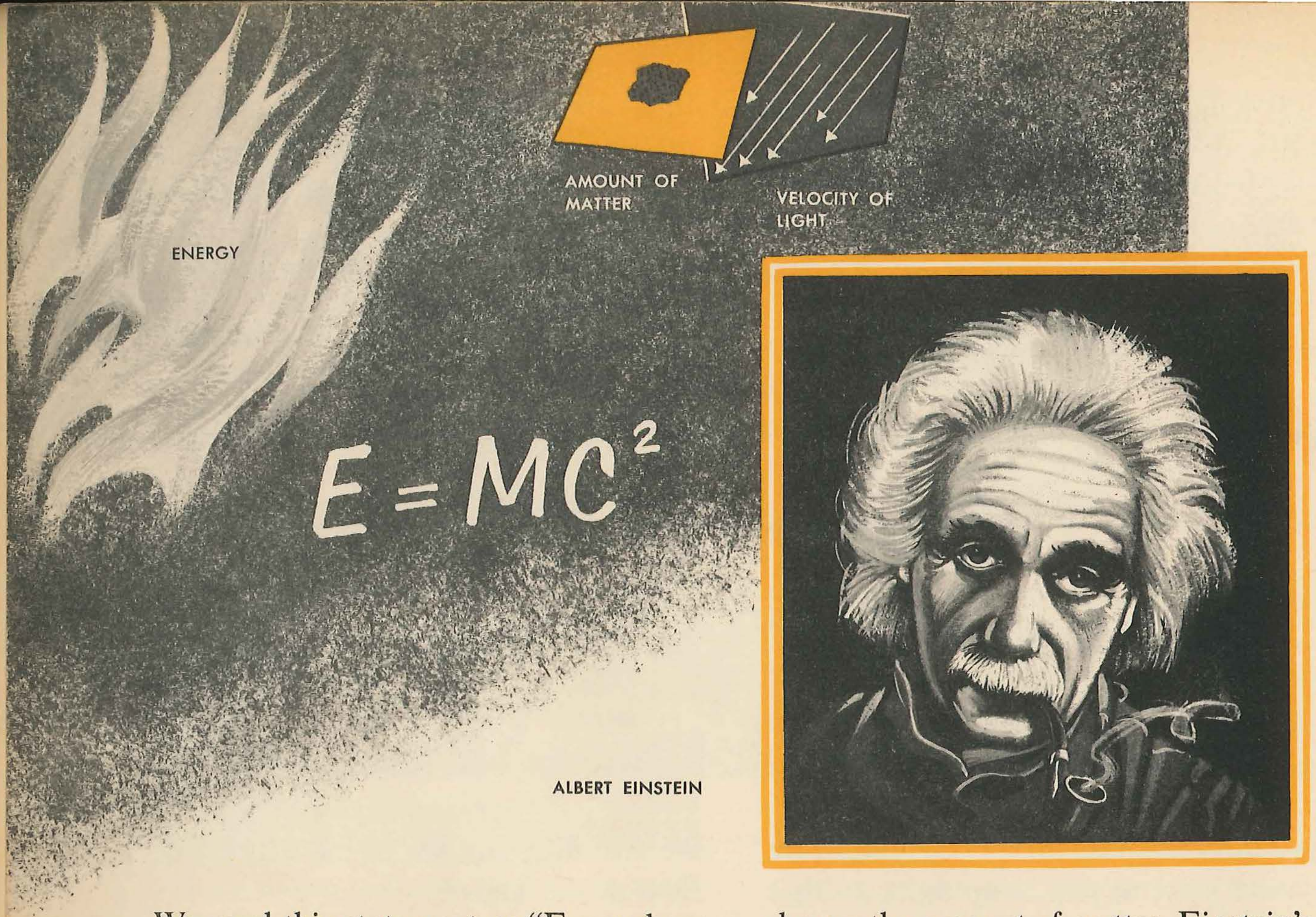


the air you needed for the fire. You would have to seal it up tight, so that absolutely no matter could get in or out. You would have to place the can on a scale while the paper burned and the can cooled off. And your scale would not show any change in weight.

In 1900, we all would have agreed that the ash and smoke and gases from the flame weighed *exactly* what the paper and air weighed to begin with. For we all thought then that there was another law of nature, called the *Law of the Conservation of Mass,* which said that no matter is ever added to the universe or taken away from it. Well, we know now that there actually *would* be a tiny loss of weight in that can. You could not have converted one half an ounce of matter into energy. But you would have converted one ten-billionth of an ounce of matter into energy. No scale in the world is good enough to show it. But you would have done it. How do we know?

When did physicists change their mind?

In the year 1905, a young German-born scientist was working in the Swiss Patent Office, checking other people's inventions. And he wrote a paper about what he called his *Theory of Relativity.* He hoped it would explain some facts about light and about the stars which had been mystifying physicists and astronomers for years. It did. It did something else, too. In this paper, Albert Einstein, one of the great scientific minds of all time, wrote a sentence which has become the most famous sentence of the twentieth century. Einstein did not write his sentence in words. He wrote it in algebra, the language of mathematics that uses letters of the alphabet to stand for numbers: $E = mc^2$.



ALBERT EINSTEIN

What does $E = mc^2$ mean?

We read this statement as "E equals m times c squared." It says that if you take a certain amount of matter and convert it into energy, you can calculate the number of foot-pounds you will get (which we have written down as E, for energy) by multiplying the number of pounds of matter you wipe out (which we have written down as m, for mass) by a certain number that is always the same (which we have written as c^2). Or, if you change energy into matter, the same formula will tell you how much mass you get in exchange for your energy.

Einstein did not just say that this is what *would* happen if it *could* happen. He said it *does* happen. All the physicists had known that energy can be stored in matter and gotten out again, but they believed that this did not change the amount of matter. Einstein's brilliant theory said that when energy is stored in matter, it takes the form of a little additional mass, and when the energy is released, the mass goes back to what it was. In other words, instead of a Law of the Conservation of Energy and a separate Law of the Conservation of Mass, we now had one law, the *Law of Conservation of Mass-and-Energy.*

Does $E = mc^2$ work for all kinds of matter?

And this suggested a very strange idea. It was not some particular little bits of energy or mass that might change back and forth. If only we know how, we could change *any* mass into energy.

No one did much about it for many years. In the first place, no one knew where to start. In the second place, scientists felt happy enough just having a tidy new theory which helped them calculate things they could not measure with instruments and which explained various odd facts they had never understood before. Most of them paid no attention to one letter in the famous equation. That was the letter c.

How much energy can we get from matter?

Now, in Einstein's theory, c stands for speed of light. Light travels at 186,000 miles per second. The expression c^2 ("c squared") means the speed of light *multiplied by itself.* It gives us a gigantic number, 34,596,000,000. If we do the arithmetic using this number, we find that from very little mass we get an astonishing amount of energy. When we burn a pound of coal in the ordinary way, we might get 10 million foot-pounds of energy. This is good. But if we could convert the whole pound of mass into energy, then by Einstein's formula we would get 30 million billion foot-pounds of energy. This is better.

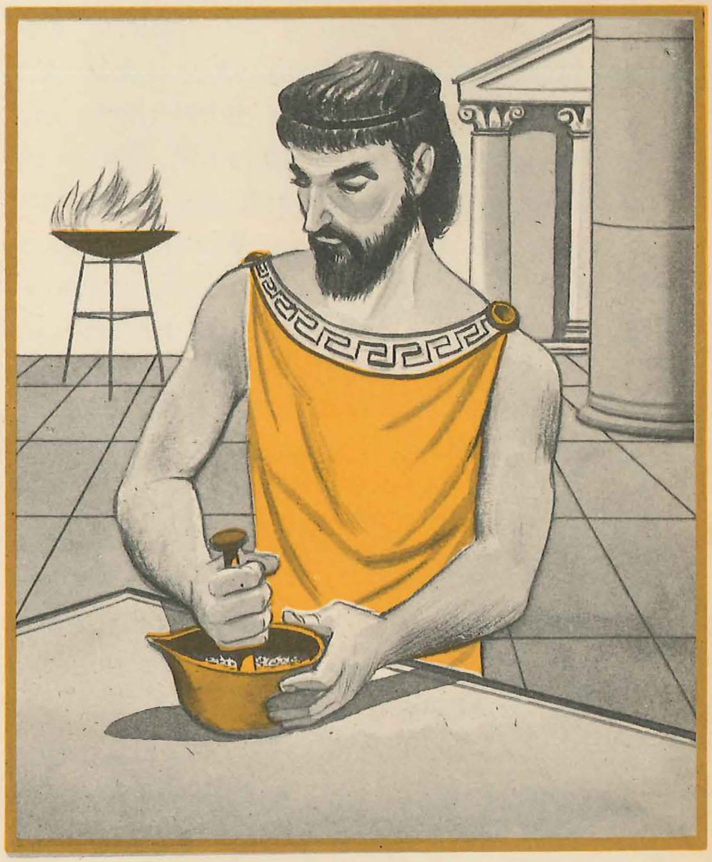
If only we know how. . .

Inside the Atom

What is matter made of?

The ancient Greek philosophers wondered what would happen if we took some solid matter — like stone or metal — and kept grinding it up into finer and finer powder. Some said that no matter how tiny the particles became, it would always be possible to break them up into still smaller particles by grinding harder. They believed that matter was made of a stuff called *hyle* (which is Greek for "stuff"), and that this was smooth right through and could be divided up endlessly.

Others said that no matter how hard or long we ground, we could not get the particles smaller than a certain size. They believed matter was made of separate hard lumps called *atoms* (which is Greek for "can't be cut"), and that these were the smallest things or particles there were.



Some ancient Greeks said matter could be ground endlessly. Others said atoms were the smallest things.

The second group was nearer to the truth, of course. Matter usually does consist of atoms. But they were wrong in thinking there was nothing smaller than an atom. And they certainly picked the wrong name for their fundamental particle. The atom can be cut.

What are elements?

For 2,200 years, no one had anything new or important to say on the subject. Then in 1803, an English schoolteacher named John Dalton began to study atoms seriously. He figured out that some things are made up of only one kind of atom. These are pure *elements.* Gold and mercury and oxygen are elements. Other things are made of two, three or even more different kinds of atoms. These are *mixtures* and *compounds.* In mixtures the different elements are simply jumbled together. Air is a mixture of oxygen and nitrogen and other gases. In compounds, atoms of different kinds are actually linked together in little groups. Water is a compound in which each oxygen atom is linked up with two hydrogen atoms in a tiny package called a water *molecule.*

What did Dalton discover about atoms?

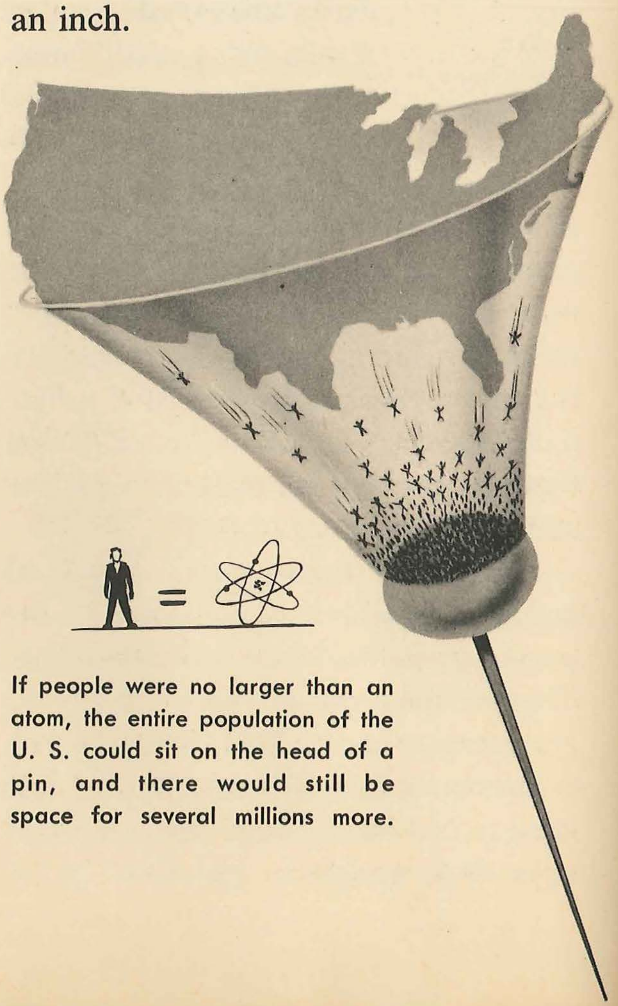
Dalton weighed and measured elements and compounds until he began to find some rules for the ways in which the atoms could be linked and separated. He was able to calculate how much different atoms weighed compared to each other. But he still thought that atoms were little pellets—too small to see and too tough to cut, but not really different from grains of dust.

Are atoms solid?

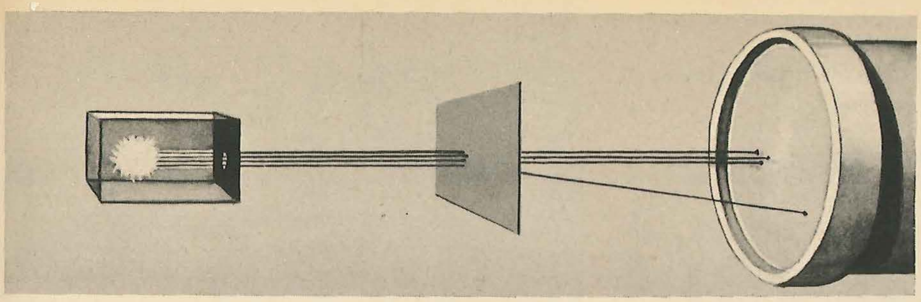
An atom — even an atom of iron in the steel armor-plate of a warship, or an atom of carbon in a diamond — is mostly empty space. The big old solid world around us is not solid at all. It is made of tiny spots of matter hanging or whirling quite far apart in open space.

Then why, if you pound your fist on the table, doesn't your hand go *into* the table-top? Because your hand, too, is empty space, and because strong electrical forces between the whirling spots hold them away from each other. Those forces, jostling the atoms in your flesh, are what you feel as the bang of your hand on the table.

We are sure of this although no one has ever actually seen an atom. Atoms are too small to see — 100 million of them in a row would take up less than an inch.



If people were no larger than an atom, the entire population of the U. S. could sit on the head of a pin, and there would still be space for several millions more.



Most of the atomic bullets go through the "solid" metal — this shows that atoms are mostly empty space.

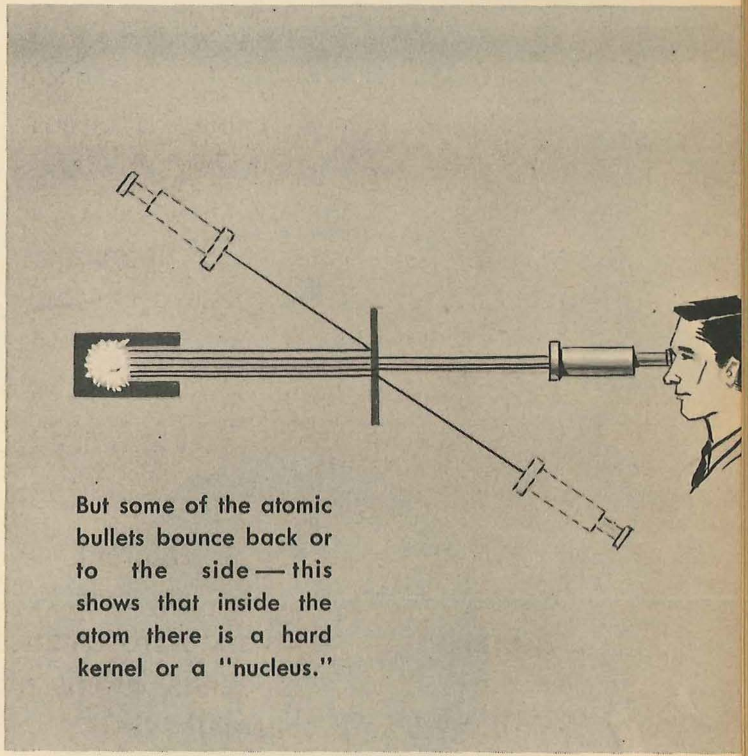
Can we see atoms?

In 1911, an English physicist named Ernest Rutherford invented a way of testing whether atoms are solid. He shot them with even smaller particles. He got his "bullets" out of atoms of the element *radium,* which Pierre and Marie Curie of France had discovered and extracted from certain rocks. Radium atoms have a strange property. They are always breaking up little by little and flinging out tiny fragments of matter and little streams of energy. Several elements do this. They are called *radioactive* elements.

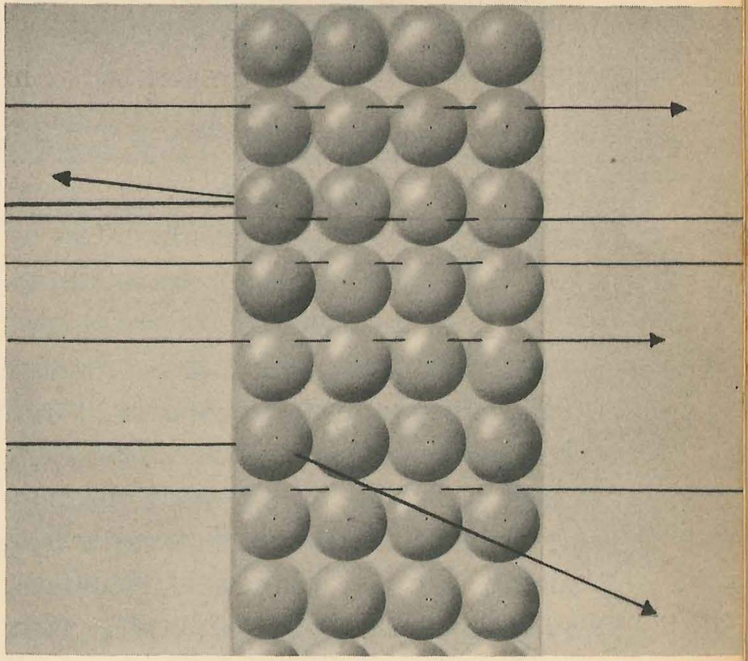
How did we learn what is inside the atom?

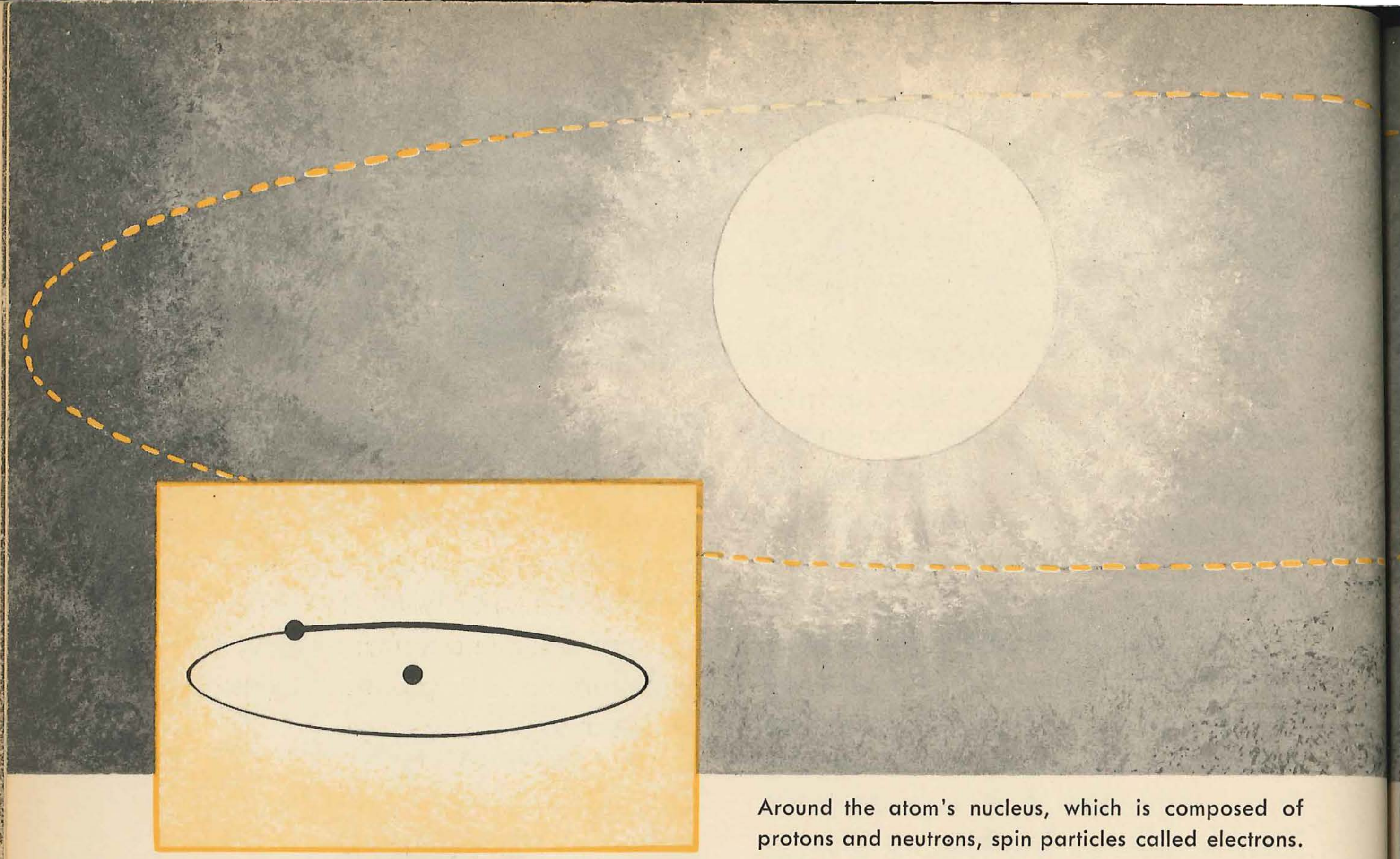
Rutherford put some radium in a sort of gun-barrel made of lead. He aimed it at a target made of a fluorescent screen, like the front of a television picture tube. In between, he put a thin sheet of pure gold — but thin as it was, it was thousands of atoms thick, and shooting at it with the atomic "bullets" was like shooting with real bullets at armor-plate fifty feet thick. Yet the atomic bullets went through, and made little sparkles on the target screen.

And some of the sparkles were way off to the side, as if the atomic bullets had ricocheted. Rutherford realized what had happened. The bullets got



But some of the atomic bullets bounce back or to the side — this shows that inside the atom there is a hard kernel or a "nucleus."





Around the atom's nucleus, which is composed of protons and neutrons, spin particles called electrons.

through easily because the gold atoms were not solid stuff, but open space. And in the middle of each atom there was a lump of mass, off which a bullet sometimes bounced. Rutherford decided to call this lump the *nucleus* of the atom, from the Latin name for the pit in a piece of fruit.

How do we look at atoms?

Now we have hundreds of different devices for studying atoms, ranging from regular X-ray machines to fantastic jungles of wires and magnets and vacuum tubes called by such names as *cyclotron* and *bevatron*. One great *synchrotron* near New York City uses four thousand tons of magnets and a huge doughnut of metal a half mile around. With these huge machines, we can glimpse a little of what is going on in the tiny universe of the atom.

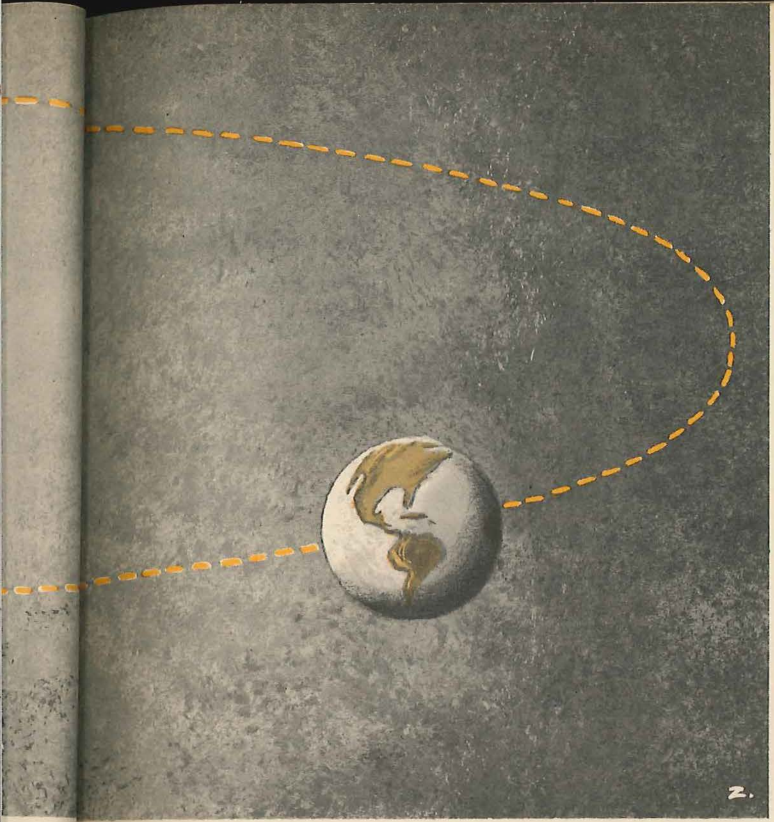
What is inside the atom?

Scientists have put together all the facts they have gathered about the atom and they have a kind of picture of it in their minds. It looks something like a picture of our solar system. In the middle of the solar system the huge sun hangs in empty space. Around it, one inside the other, in paths or "orbits" like circles pulled out of shape, spin the planets, like our earth and Mars and Saturn.

In the middle of an atom, hanging in empty space, is the nucleus. Around it, in orbits like circles pulled out of shape, spin other tiny particles.

How big is the nucleus?

The nucleus is so small it is hard even to think about how small it is. The atom itself is small—there are 6,000,000,000,000,000,000,000 atoms



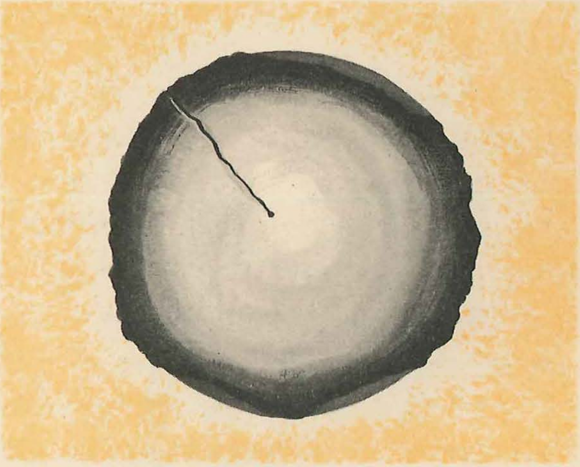
The action of electrons spinning around the nucleus is much like the orbit of the earth around the sun.

in a drop of water. If you had that many strawberries, you could cover the whole world with a layer of strawberries seventy-five feet thick. And the nucleus takes up only $\frac{1}{1,000,000,000,000}$ of the space of the atom. If the nucleus were the size of a strawberry and you put it down in the middle of a big football field, right on the fifty-yard line, the outer "planets" of the atom would be going around in orbits way out over the spectators' heads, or even behind them.

But even though the nucleus takes up only a trillionth of the space in an atom, it has almost all the mass of the atom. Thus it is tremendously heavy for its size. A nucleus the size of a strawberry would weigh about 75 million tons. If you did put it down in the middle of a football field, the earth could not hold it. It would simply crush its way through sand and rock, down and down to the core of the world.

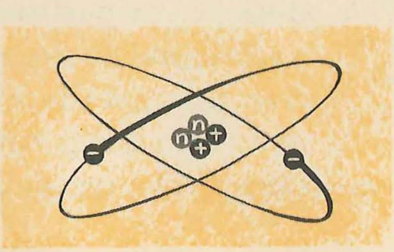
What is the nucleus made of?

The nucleus is mostly made of two kinds of particles, *protons* and *neutrons*. The outer planet-particles are *electrons*. There are two kinds of electricity, which we call *positive* and *negative*. Two things that have positive electric charges push each other away. So do two things with negative charges. But if a positively charged thing and a negatively charged thing are near together, they pull at each other very strongly.



A nucleus that was the size of a strawberry would smash the earth's crust by its enormous weight.

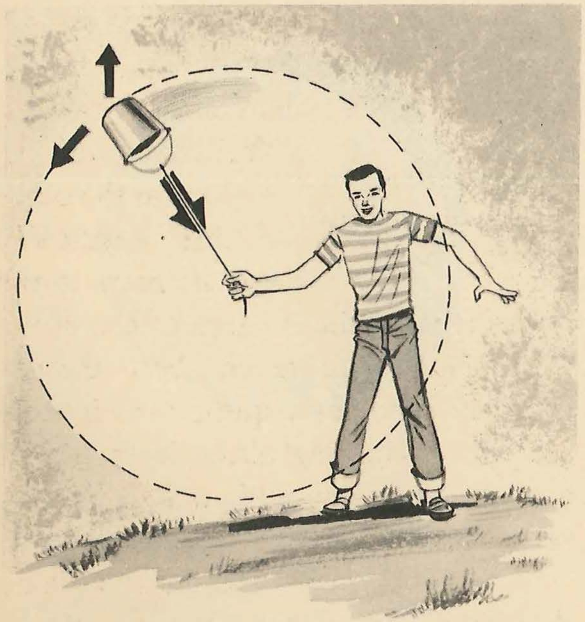
The proton has a positive electric charge of a certain strength. The neutron has no electric charge at all. The electron, which is about 1,800 times lighter than the other two particles, has a negative electric charge — just as



HELIUM ATOM

strong as the proton's, but the opposite kind. The nucleus or "sun" of the atom, therefore, has a positive charge. The outer electrons or "planets" have a negative charge. And the whole atom itself usually has no charge, because there are just as many protons in the nucleus as electrons whirling around it, so the charges balance or cancel each other. In the ordinary sodium atom, which is one of the atoms in salt, there are eleven protons and twelve neutrons in the nucleus, and eleven electrons going around in orbit.

By now, you will have thought of two questions. One is easy and one is hard.



The pull of the nucleus keeps the electrons in orbit just as your arm keeps the weight in its orbit, too.

Why do the electrons keep flying around the nucleus?

If things with opposite charges attract each other, why doesn't the positive nucleus pull the negative electrons right down into it and just collapse the atom? Easy. The speed of the electrons makes them keep trying to fly off, away from the nucleus. Tie a weight to a string and whirl it around fast. You can feel the pull of the weight trying to fly away from your hand at the center. You have to pull a little to keep the weight in orbit. The electrical pull of the nucleus keeps the electrons in their paths, just as the pull of the sun's gravity keeps the earth in its orbit.

And if things with the same charges push each other away, why don't the protons in the nucleus just go flying off from each other in all directions? That one is hard. That is where atomic energy comes in.

Is atomic energy a special kind of energy?

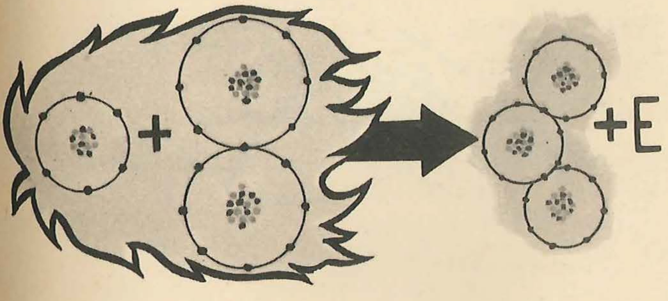
By the way, if we were going to be very careful about words, most energy really could be called *atomic energy*. Because, as Einstein showed us, when energy flows around the universe it is always changing the mass of atoms. But when we think about the insides of the atom, we can see that there are two sorts of energy. One has to do with the outer electrons. The other has to do with the nucleus.

How do atoms form chemicals?

When two different atoms are linked together in a chemical compound, the nucleus of one does not join the nucleus of the other. Instead, some of the outer electrons change their orbits. Sometimes the two nuclei will share a few of these electrons. When a carbon atom forms the gas called methane, for instance, it shares electrons with four hydrogen atoms. Or sometimes one nucleus steals an electron from the other by a complicated magnetic trick, and this leaves the thief-atom negatively charged and the victim-atom positively charged, so they stick together. This is how sodium and chlorine combine to make ordinary salt. It is as if the poor sodium atom kept following the chlorine atom around in the hope of getting its electron back. This kind of linking is called a *chemical* bond.

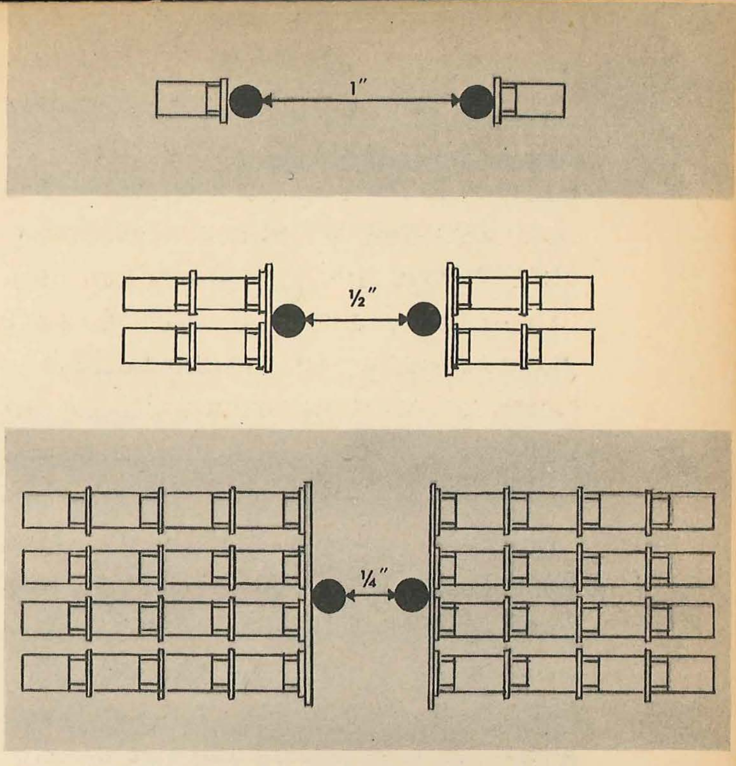
What is chemical energy?

Sometimes when you make or break a chemical link, energy is given out, and this is called *chemical energy*. When an atom of carbon in a chunk of coal links up with two atoms of oxygen from the air, a compound called carbon dioxide — a gas with no color or smell — is formed, and at the same time heat-energy and light-energy are released. In other words, you have a fire. But this does not disturb the carbon nucleus or the oxygen nuclei.



Heat given off when a carbon atom joins with two oxygen atoms is a simple form of chemical energy.

If you actually change the nucleus of an atom in order to get energy, you are doing something quite different. We ought to call this *nuclear energy*, but we usually just call it *atomic energy*.



Things with the same electric charge push each other apart. When you divide the *distance* between them by 2, you multiply the *push* between them by 2 x 2.

Where does "atomic energy" come from?

We wish to turn matter into energy. Well, then, we have to look at the place where practically all the mass in the universe is — the nucleus of the atom. We do not know much about the nucleus yet. One of the questions scientists are still wondering about is that hard question of yours: What holds it together?

Something must. We know how strong the forces are that push apart things that have the same electric charge. The closer together the two things are, the more powerful is the force that pushes them away from each other. If there is a certain push between them when they are 1 inch apart, there will be 4 times as much push when they are ½ inch apart, and 16 times at ¼ inch, and 64 times at ⅛ inch, and 256 as strong at $1/16$ inch. At that rate, you can imagine how hard the push is between two protons rammed into a nucleus $\frac{1}{2,000,000,000,000}$ of an inch apart. It takes a lot of energy to keep them side by side.

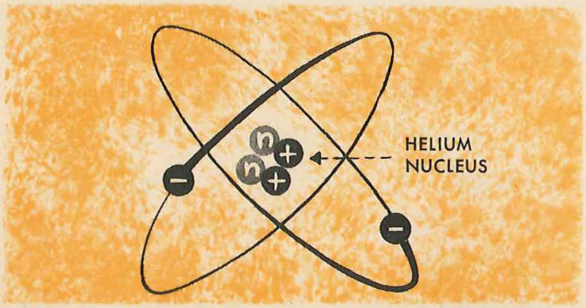
What holds the nucleus together?

This energy is called *binding energy.* There is only one kind of atom that does not need any binding energy. That is the atom of hydrogen gas, which only has one proton in its nucleus. Some of the heavier kinds of atoms, with dozens of protons in their nuclei, have to have enormous amounts of binding energy. Where do they get it?

From mass. No one knows how a nucleus converts some of its own mass into energy in order to pull itself together. But physicists all agree that this is what happens. They can prove this by very carefully measuring the mass of an atom. Except for hydrogen, every atom weighs just a little bit less than it *ought* to.

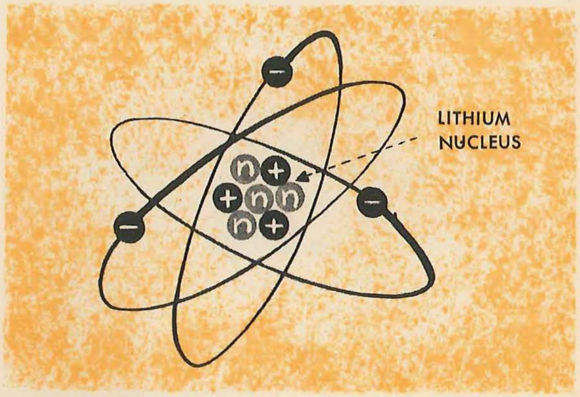
How much binding energy is in the nucleus?

Take helium gas, for instance. The helium nucleus contains two protons and two neutrons. A proton by itself weighs 1.00758 of the tiny "mass units" that scientists have invented for these measurements. A neutron weighs 1.00894. So the whole helium nucleus ought to weigh 4.03304. Instead, it weighs 4.00279. More than $\frac{3}{100}$ of a "mass unit" are missing. Using Einstein's $E = mc^2$ formula, we can calculate how much energy this is — what the scientists call 28 million "electron volts." This is only a tiny fraction of a foot-pound. But it is what keeps the universe from going *whoosh!* and turning into hydrogen. And it is what lets us turn matter into atomic energy.



How many kinds of atoms are there?

There are hundreds of different kinds of atoms in the universe. One way of sorting them out is to find out how many protons they have in the nucleus. All the atoms with one proton are *hydrogen* atoms. All with two are called *helium.* All with three, *lithium.* Four, *beryllium.* Five, *boron.* Six, *carbon.* Seven, *nitrogen.* Eight, *oxygen.* And so on up to ninety-two, which is *uranium.* That is the heaviest kind of atom found in nature, though we have made a few heavier ones with our cyclotrons and atomic furnaces.



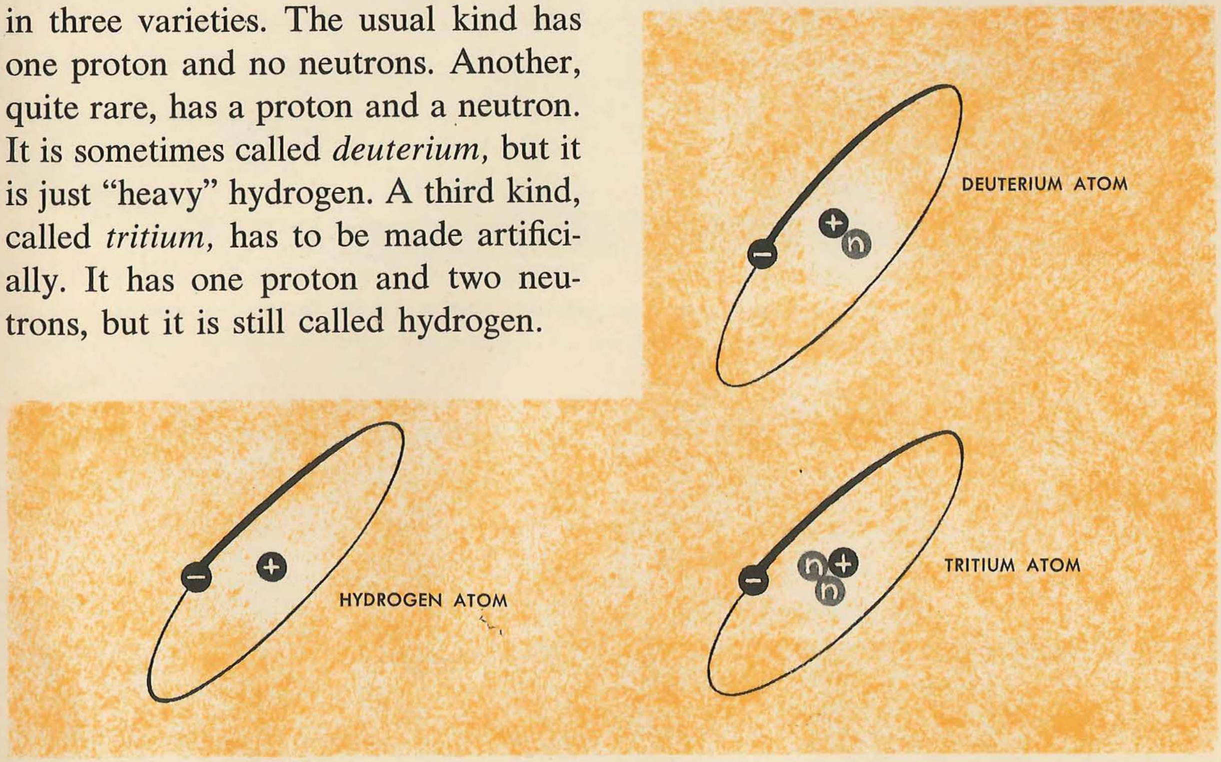
Each kind of atom with a certain number of protons is a different *element*. Until recently, we thought we were saying all we had to say about any atom if we just told what element it was. This, of course, is not so hard to do, because the number of protons in the nucleus is the same as the number of electrons out in orbit. These electrons are what make the atoms link chemically with other kinds of atoms or refuse to link with them. So clever chemists can always separate different elements.

Are all the atoms of an element the same?

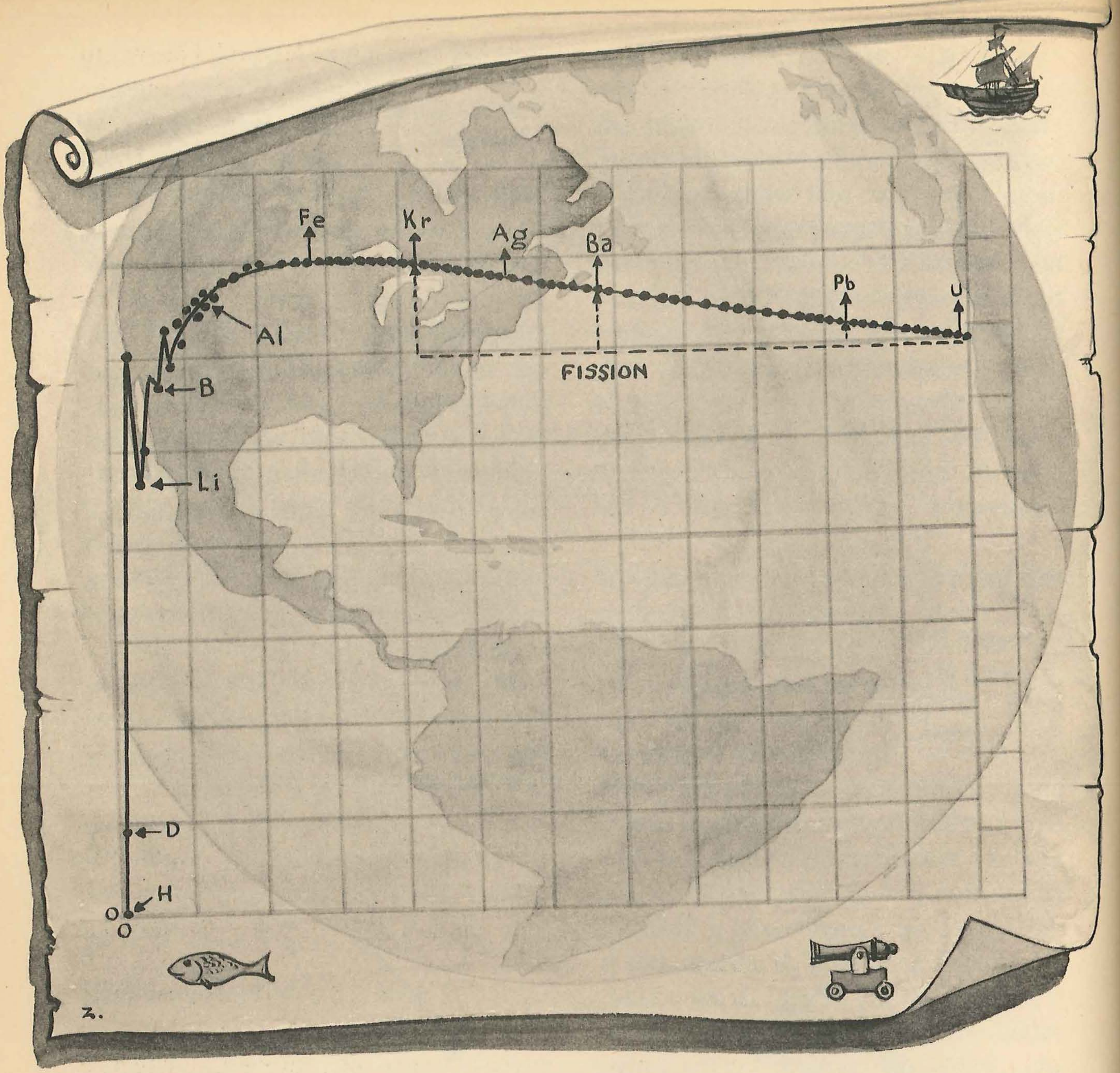
What is an isotope?

But there is another kind of particle in the nucleus — the neutron. Atoms with the same number of protons may come in different varieties, with different numbers of neutrons. Even the lightest and simplest element, hydrogen, comes in three varieties. The usual kind has one proton and no neutrons. Another, quite rare, has a proton and a neutron. It is sometimes called *deuterium,* but it is just "heavy" hydrogen. A third kind, called *tritium,* has to be made artificially. It has one proton and two neutrons, but it is still called hydrogen. Each of these varieties is called an *isotope*. The name was taken from the Greek words meaning "the same place," because isotopes of the same element always appear together in the chemists' lists. And that is more important than it sounds. Since different isotopes of the same element have the same number of outer electrons, they are just the same in chemical linkings and unlinkings, so that chemists have had a difficult time separating them. And since different isotopes of the same element behave quite differently when it comes to converting mass and releasing nuclear energy, they *must* be separated.

We have some wonderful machines that actually sort out atoms by weight. But they can only do it with a few atoms at a time.



The usual hydrogen atom has 1 proton; deuterium has 1 proton, 1 neutron; tritium has 1 proton, 2 neutrons.



If you dig for buried treasure, the best thing you could possibly have is a map. The binding energy curve, a chart of all the isotopes in the world, tells us where we can dig energy treasure out of the nuclei of atoms.

What is the "binding energy curve"?

This, however, is enough to give us the facts we need to make a great chart of isotopes called the *binding energy curve*. This chart tells us how much mass is "missing" from the nucleus of each of the hundreds of isotopes we have found or made. In other words, it tells us how much matter each kind of nucleus has mysteriously converted into energy to keep itself together.

This chart is why all the physicists were so excited when word spread that Hahn had turned the metal uranium into the metal barium. For the chart is like a map of buried treasure. It tells us where to dig for atomic energy.

Did the big atoms have the most binding energy?

It tells us that ordinary hydrogen has no mass missing. It tells us that helium, the next heavier element, has quite a lot missing. As we go up through heavier and heavier kinds of atoms, we find more and more mass missing *for each particle in the nucleus* — up to a point. Up to a point — the element iron — and then, strangely enough, we find less and less mass missing for each particle in the heavier and heavier isotopes.

When we get to the heaviest element — the three isotopes of uranium — and look up how much mass is missing from the 234, or 235, or 238 nuclear particles — we find that much less of it has been turned into energy than in such middleweight elements as barium.

Think for a moment what this means.

How can we get at some binding energy?

It means that if we split up a uranium atom into two pieces, we will get two smaller atoms — and something else. There are 92 protons in the uranium nucleus. Let us say the two pieces happen to be not quite equal. One might have 36 protons in it — that would be the gas krypton. The other would have the remaining 56 protons — it would be barium. When you look at the chart you see that barium and krypton have *more mass missing* from them than uranium. So suddenly, some mass has disappeared from the universe.

And Einstein's formula tells us what has become of it. It has turned into energy — into the tremendous force with which the fragments of the uranium fly apart.

Why doesn't binding energy stay inside the atom?

Maybe it is a little hard to see why this is energy we could use. Why doesn't this mass turn into energy that the nucleus uses inside of itself? As a matter of fact, it was hard for some physicists to be sure about this for a while. One answer is that binding energy does not work by brute force. It is something like the law that says you can't leave the country if you owe money to the government. The binding energy was energy that was given off when the protons and neutrons

Protons and neutrons owe energy to the nucleus and they are supposed to stay there until the debt is paid.

were packed together, and ordinarily they cannot get away unless this energy, this missing mass, is restored to the nucleus. But even if you can't leave legally, you could always *break* out. That is what happens when we split the atom.

And that is why the chart means this also: If we could mash a couple of hydrogen nuclei together so as to form a helium nucleus, we would also wipe out some matter. We would wipe out more matter, in fact, than by splitting uranium. The energy would be prodigious. It would be like making a sun. For this *is* how the sun gets its energy.

Atom Smashing

Who discovered radioactivity?

In 1896, before we knew anything about $E = mc^2$ or what the atom is like, a French physicist named Henri Becquerel had a slight accident in his laboratory. He was testing some uranium compounds for something and discovered that they gave off energy all by themselves. Soon after that Pierre and Marie Curie began to discover a whole group of new elements that did the same thing. Madame Curie named this strange behavior *radioactivity.*

For a long time, nobody was sure how radioactivity worked. Many experiments were done to find out just what these mysterious "rays" were. Some of them at last turned out to be helium atoms with their electrons knocked off. Some turned out to be fast-moving electrons. Some turned out to be real rays like very powerful X-rays. But what were they doing in those atoms? And why did they come out?

Do atoms ever split by themselves?

It slowly dawned on the scientists that what they were looking at were *atoms breaking down.* This was a rather frightening idea, for two reasons. In the first place, everyone at that time still thought atoms were unbreakable, everlasting little pellets. This showed they were not. And if pieces broke off an atom, what was left must be a different atom. That meant elements were changing into other elements. And if elements changed into other elements when particles flew out, then atoms probably were not the particles that "could not be cut" (as their name said), but were bundles of still smaller particles.

Why was radioactivity important?

In the second place, the particles flew out with great energy and the rays were very energetic, too. These atoms seemed to be *making* energy, which everybody in

The French physicist, Antoine Henri Becquerel (1852-1908), discovered natural radioactivity, the invisible radiation of uranium. With Pierre and Marie Curie, he won the Nobel Prize in physics for his great discovery.

The strange rays from uranium blackened a photographic film right through a light-proof cover, Becquerel found.

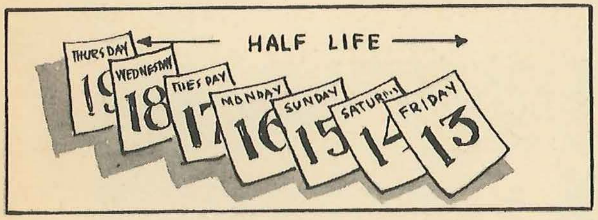
Pierre Curie of France (1859-1906) and his wife Marie (1867-1934) were the discoverers of radium in 1898. In addition to sharing the Nobel Prize with Becquerel and her husband in 1903, Marie Curie received the Nobel award again in 1911, in chemistry.

Let's pretend that you were very rich and that you had the very large sum of one million dollars, even after taxes.

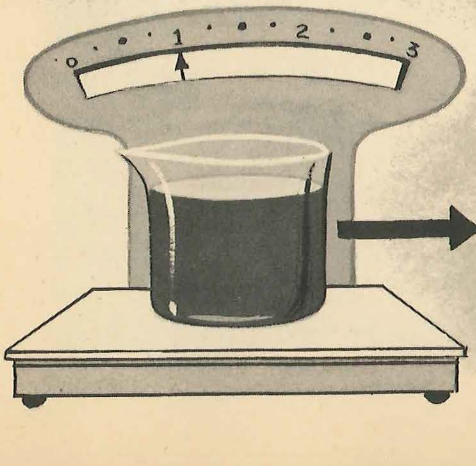
And now let us also suppose that you have promised to give away half of all your money on every Friday of the week — even on Friday the thirteenth.

Then on the first Friday, you will give away $500,000. On the second Friday, you will give away $250,000 more. On the third Friday, $125,000 more.

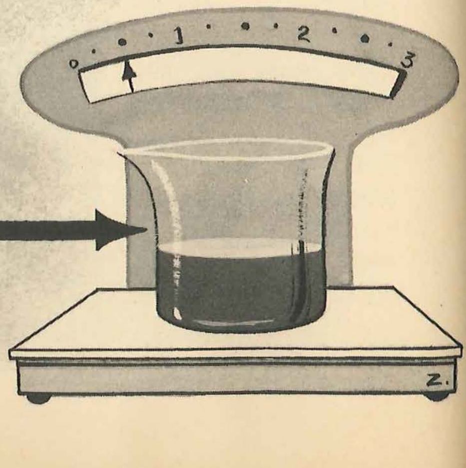
Then we say that the "half-life" of your money is one week, because in one week, one half disappears.



But no matter how much you give, you will never go altogether broke.



U-238 = 4,500,000,000 YEARS
RADIUM = 1,620 YEARS
FRANCIUM = 21 MINUTES
THORIUM = 14,000,000,000 YEARS
POLONIUM = 138 DAYS
NEPTUNIUM = 2⅓ DAYS



And — every radioactive isotope has its own "half-life."

those days *knew* was all wrong. When Einstein came along and said that this energy was converted from mass, it seemed like the best explanation.

So a lot of what we now know about atoms came from that laboratory accident.

Now all those radioactive atoms were quite heavy. It seemed that a heavy nucleus was not too sturdy. This suggested that if we could only smash up heavy atoms, instead of letting them decay slowly by themselves, we might change one element into another and perhaps even release energy much faster. But we had nothing with which to smash them.

Why are neutrons good atomic bullets?

The neutron is a quiet little particle. There are probably more neutrons in the universe than anything else, but it was not till 1930 that we found them — hiding right in the middle of everything. For years, physicists had been trying to make a picture of the atom that would explain the things atoms did. They tried all sorts of wild combinations of the positive proton and the negative electron. Then an Englishman named James Chadwick suggested, "Why not try drawing it with a particle a little bit bigger than the proton but without any electric charge?" Everyone realized this was the answer. And they realized that here, also, was the thing with which to smash heavy nuclei.

The problem is to hit the nucleus. Suppose you shoot at it with a positively charged proton. As it passes the negatively charged electrons, they will pull it to one side. As it approaches the positively charged nucleus, that will push it away. Suppose you shoot an electron. The positive nucleus will certainly pull the negative electron toward it. But electrons are too light. They cannot do enough damage. The neutron is heavy and it will not be pulled off its course.

How do we split uranium atoms?

So physicists set up various machines for using other particles to bounce neutrons out of the nuclei of light metals like beryllium. And they started shooting.

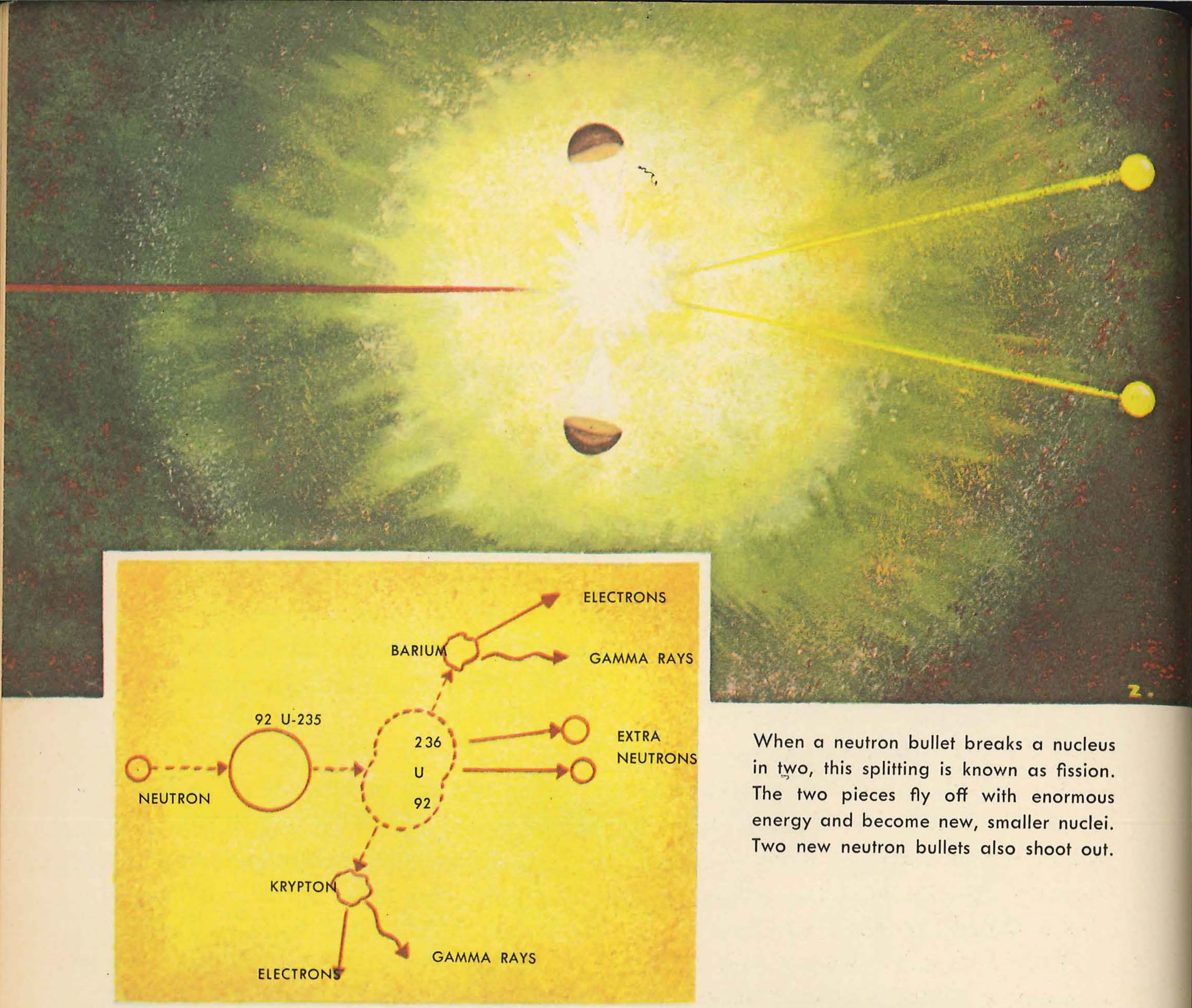
They kept shooting for seven years. All sorts of things happened. They made new elements, heavier than uranium. They made old elements radioactive.

And one day in January 1939, Otto Hahn found a little barium in the uranium that he had been bombarding with neutrons. The news spread that the uranium nucleus had been split, and young Dr. Dunning, remembering the binding energy chart, rushed up to his laboratory to measure the release of nuclear energy.

What happens when a uranium atom splits?

When a neutron hits a uranium nucleus, one of three things can happen. (1) It may bounce. That's that. (2) It may just stay there. Nothing would happen till later. So we will think about this. (3) It may break the nucleus apart.

Suppose a neutron hits a nucleus of one of the three ordinary isotopes of uranium. This is the isotope with 92 protons and 143 neutrons in it — called



When a neutron bullet breaks a nucleus in two, this splitting is known as fission. The two pieces fly off with enormous energy and become new, smaller nuclei. Two new neutron bullets also shoot out.

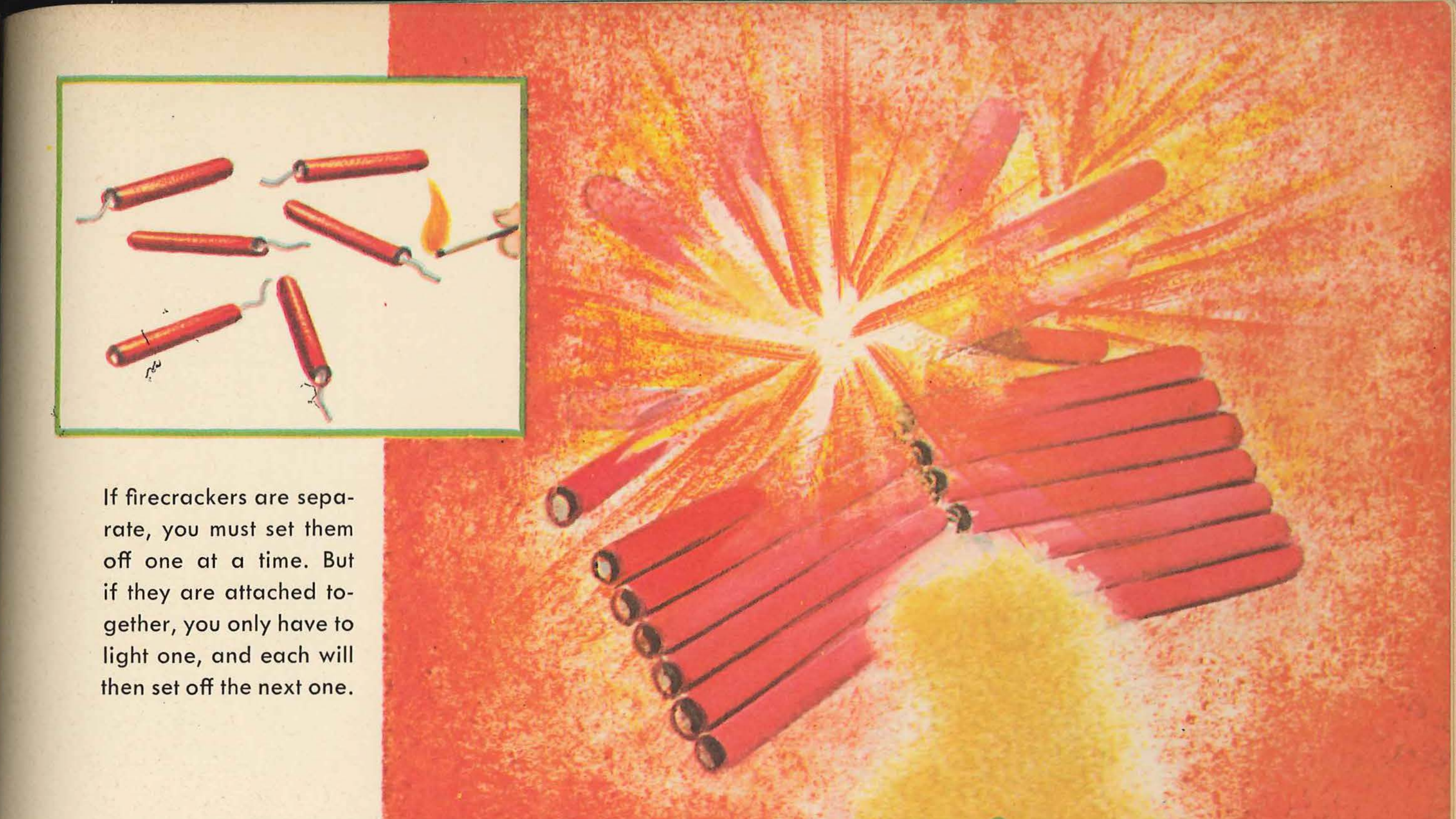
U-235. The new neutron makes it U-236. But for some reason, U-236 never stays together. It bursts into pieces. There are many ways it can break. Suppose this time the biggest piece is a barium nucleus, with 56 protons and 88 neutrons. Another piece is krypton, with 36 protons and 54 neutrons. And there are at least two extra neutrons by themselves. *They* are *very* important. And there is a lot of energy, which makes all the pieces shoot off at terrific speeds.

This is called *fission*.

What is a "chain reaction"?

It is very nice to be able to smash atoms. But it is not a useful thing to do unless you get more energy out of it than you put into it. If you have to keep a building full of equipment pumping neutrons into uranium to split a few nuclei, you are just playing.

Think back for a moment to the paper-burning experiment. You touch a lighted match to the corner of one sheet. The paper catches fire. The flames spread. You do not have to set each



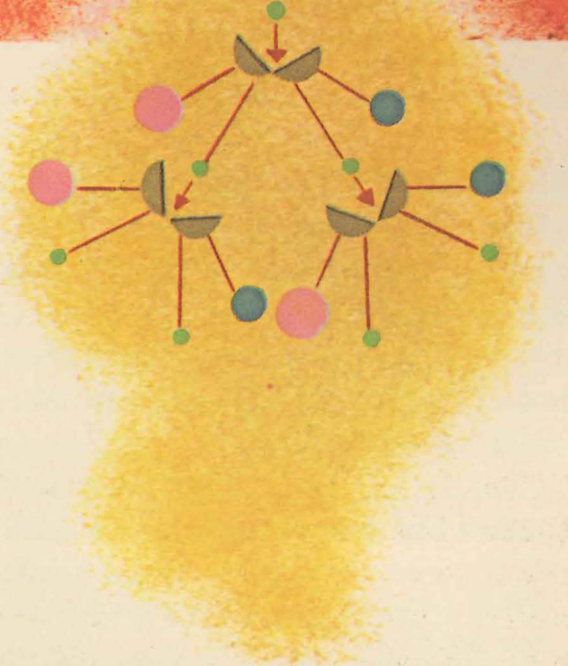
If firecrackers are separate, you must set them off one at a time. But if they are attached together, you only have to light one, and each will then set off the next one.

part of the paper on fire separately. You just heat up one small bit of it until that bursts into flame. The heat from that flame starts the next few fibers burning, and they light the next bit, and so on. This is called a *chain reaction.*

That is what we want to do with uranium. We need a chain reaction in which each bursting nucleus will shoot out neutrons that break up other nuclei near it. The two loose neutrons that fly out in the fission of a uranium nucleus give us atomic energy we can use.

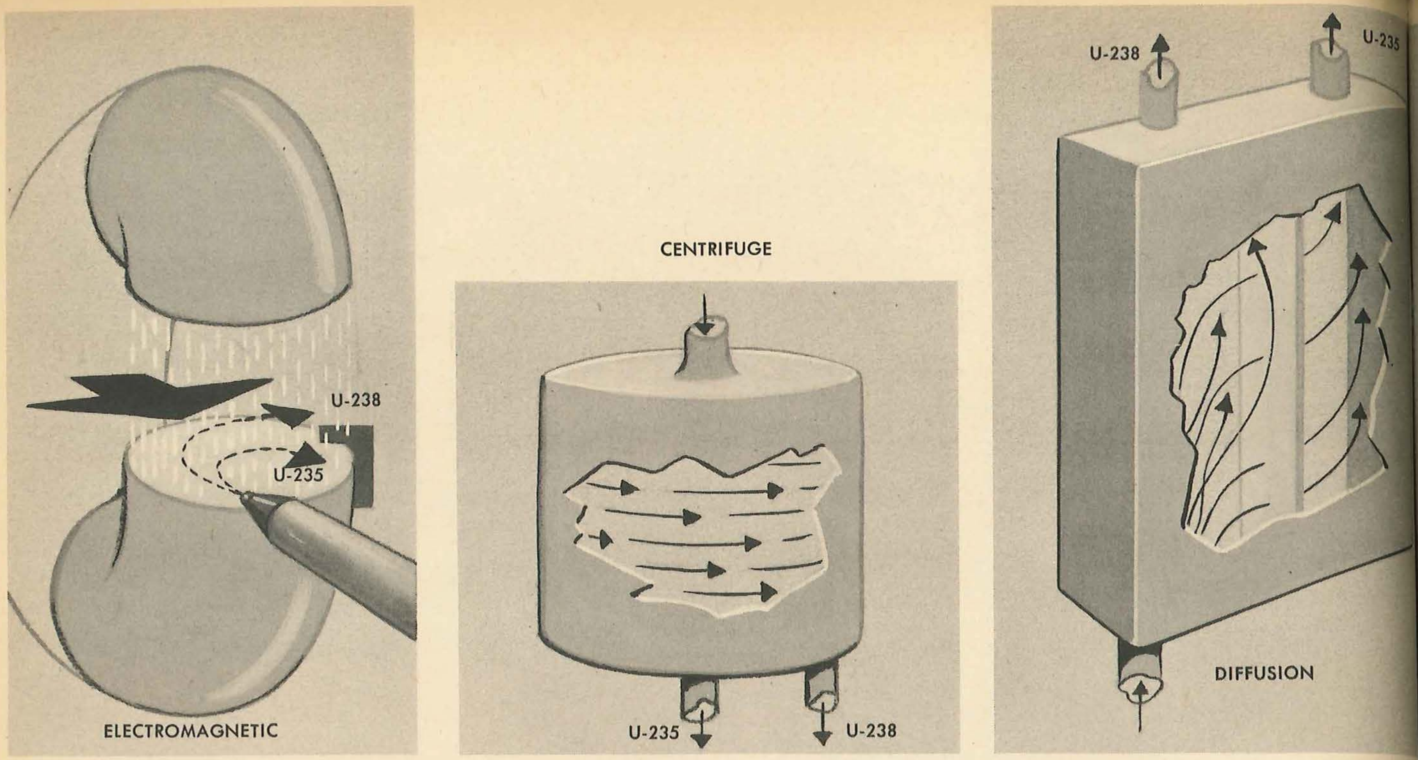
What do we need to make a chain reaction?

But now suppose — as we again think of the experiment with the match and the paper — that the paper is damp. Each bit of paper would need so much heat to get it lit that the sections next to it would have burned away before it got started. The fire would go out.



A chain reaction is something like the firecrackers that are attached to each other. When a uranium atom splits, it shoots out neutron bullets that split nearby atoms, which split other atoms, and so forth.

In the same way, we need the right isotope of uranium for our atomic chain reaction. It has to have a nucleus that splits easily and that shoots out loose neutrons. The U-235 isotope is excel-



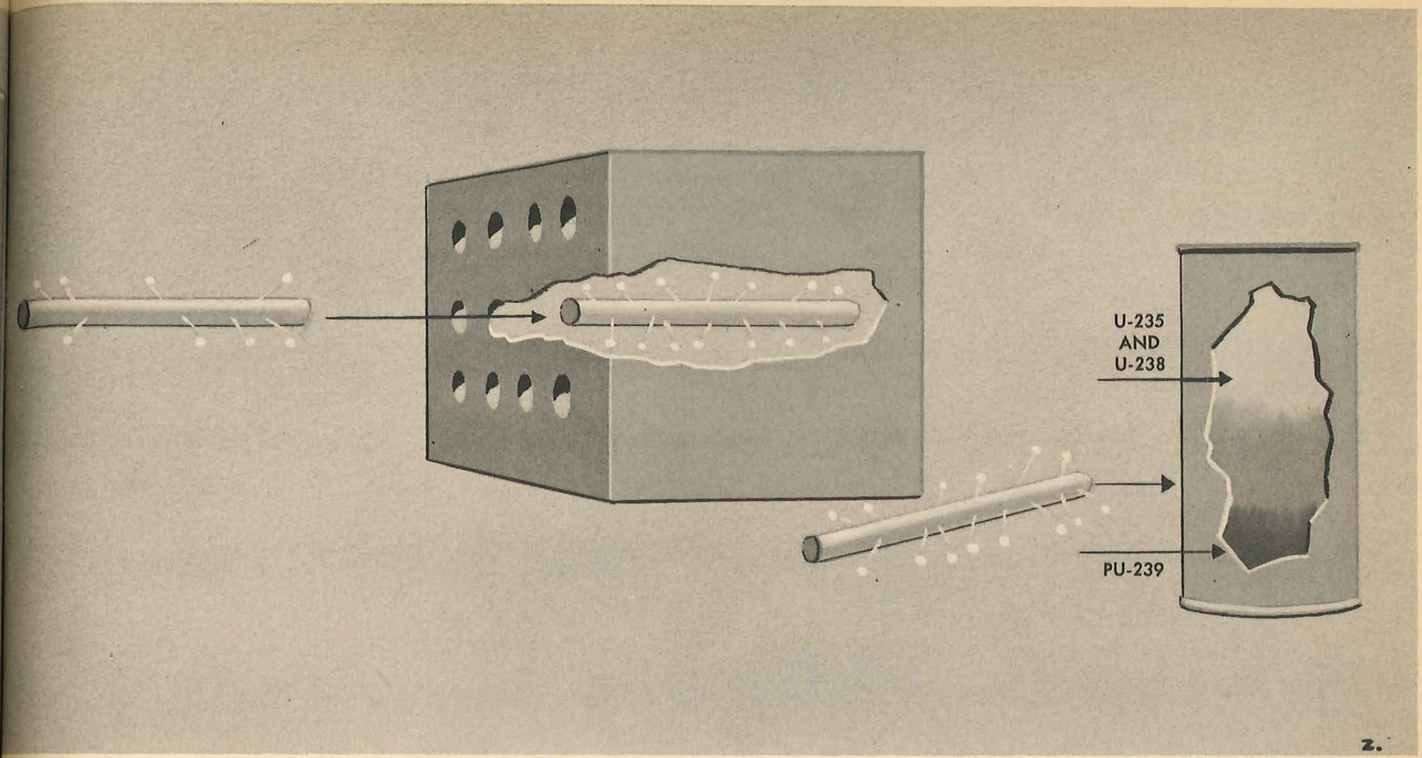
Scientists have figured out three ways to separate U-235 from U-238. In the electromagnetic way, the uranium is shot between the poles of a magnet, which separates the heavier atoms from the lighter ones. In the centrifuge way, the uranium is whirled around and the heavy atoms swing to the outside. In the diffusion way, more light atoms seep through the divider than heavy ones. Separation is necessary to make atomic fuel.

lent. But U-235 is hard to come by. No matter where natural uranium comes from — the Congo or Canada or Russia or in meteorites from outer space — it always contains the same amounts of its three isotopes. And less than a hundredth of it is U-235.

What isotopes are good atomic fuel?

Another uranium isotope, U-234, only shows up in faint traces. We can hardly tell it is there. More than 99 per cent of uranium is the heavy isotope, U-238, with 92 protons and 146 neutrons. Unfortunately, it is like damp paper. The neutrons crash into the U-238 nucleus — and stay there. This is not bad. It has its uses. But it will not keep the atomic fire going.

Will other elements or isotopes work? Yes — a man-made element called *plutonium* is excellent atomic fuel. Plutonium has 94 protons and 145 neutrons. We make it by putting U-238 in an atomic oven and "cooking" it in neutrons, so to speak. When a neutron hits the U-238 nucleus and stays there, it gives us a new uranium isotope with 92 protons and 147 neutrons. That is just too many neutrons, and this is a very shaky nucleus. But it does not break up. Instead it soon begins to break down. One of the neutrons mysteriously turns into a proton, and an electron — of all things — suddenly shoots out of the nucleus. Now we have a new element called *neptunium,* with 93 protons and 146 neutrons. But this nucleus is still rather rickety. Again a neutron changes into a proton and an electron pops out. Now we have plutonium.



Scientists have found a way to change uranium-238 into the more useful atomic fuel plutonium. The U-238 is put into a reactor where it is bombarded with neutrons from U-235. Many of the U-238 atoms are built up into plutonium-239 atoms, which can be separated chemically. At one time, scientists thought that plutonium was an artificial element, but we now know that it occurs naturally and is found in the mineral pitchblende.

Can we make atomic fuel?

But in order to have it, we first have to have a good atomic oven with plenty of neutrons. In other words, a chain reaction. In other words, U-235. That was the problem that nagged at American scientists in the years between 1939 and 1942.

Professor Fermi was sure he could build an atomic furnace that would work — and which could be used as an oven to cook up plutonium. Other scientists had calculated that if only they could get enough plutonium or enough U-235, they could make a bomb that would knock America's enemies right out of the war.

For during these years, Hitler's armies beat down nation after nation in Europe, and the Japanese struck without warning at Pearl Harbor and conquered hundreds of islands in the Pacific. Our scientists were afraid that the German scientists would make an atom bomb for Hitler, and that this cruel madman would rule the world.

Working day and night, chemists and physicists tried to invent a way of separating enough U-235 to start an atomic furnace.

How do we separate isotopes?

One group said the way to do it was the way it was done in a mass spectrometer, by shooting electrically charged streams of uranium atoms between the poles of magnets. The government spent millions and millions of dollars to build *electromagnetic separators* at an out-of-the-way place in Tennessee called Oak Ridge. It was, and is, a good factory for separating isotopes, but it could not make enough U-235.

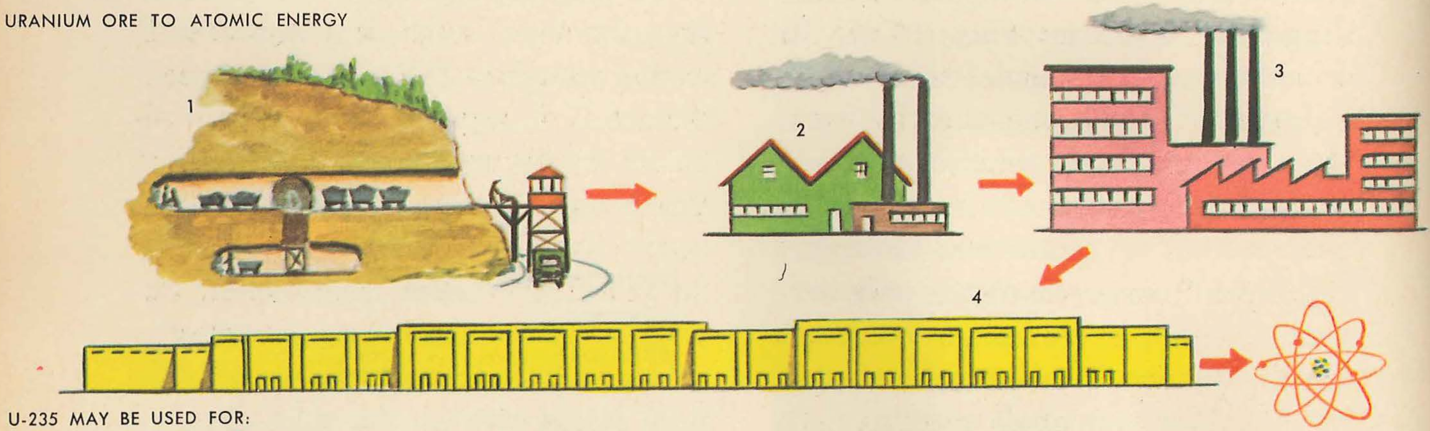
Another group said the way to do it was by *centrifugal force* — the force that makes things try to fly outward when they are whirled around in a circle. If we could make a gas or steam with uranium in it, and whirl it around in a tank, the compounds made with heaviest uranium atoms would go to the outside and we could pump them off. The Government had a factory built to try this, but it did not work well.

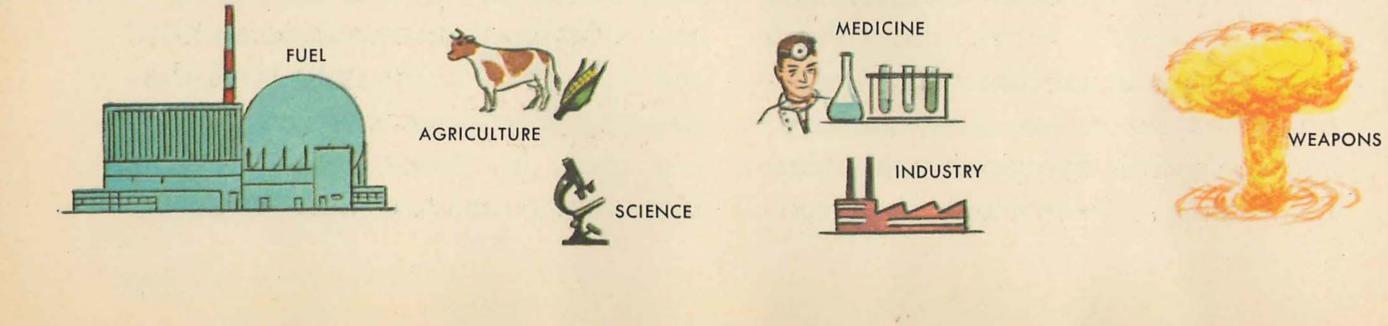
What is gaseous diffusion?

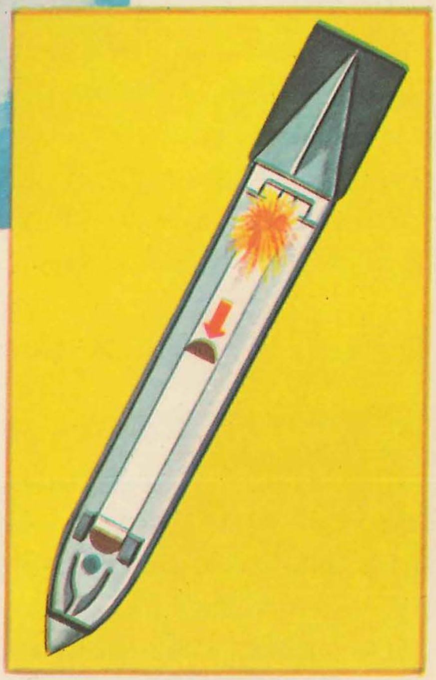
Professor Dunning and his Columbia group said the way to do it was to find a compound of uranium that was a gas, and put it in a tank with a porous wall — a wall with thousands and thousands of tiny holes in it — holes so small it would be hard for the gas to leak through. The particles of compound would be banging around in the tank, and the ones made with heavier atoms would be moving more slowly than the lighter ones. So it would be the fast, light ones that would have the better chance of pushing through the porous wall — where they could be collected on the other side. Of course, some of the heavier particles would also get through, so we would have to do the filtering over and over again in tank after tank.

The gas that had to be used was a compound called *uranium hexafluoride*. It is a vicious stuff. It would eat right through ordinary tanks and pipes and pumps like a horrible acid. So for a long time, the Government held back. Then it told Professor Dunning to go ahead and design a huge factory to be built out of special materials at Oak Ridge. More millions of dollars were spent—and the *gaseous diffusion plant,* known in wartime code as K-25, worked.

(1) Mining it. (2) Milling it. (3) Refining it. (4) Separating U-235 from U-238 in a gaseous diffusion plant.







At Bikini atoll in the Pacific, the U.S. set off an atom bomb under water. The cross section shows how an A-bomb works.

What does an isotope separation-plant look like?

It is still working. It is an extraordinary place. Miles and miles of empty corridors lined with panels of dials and signal lights — miles and miles of tank rooms and pump rooms with no man to be seen — hundreds of miles of wires and automatic machinery — and every once in a while, a man will come down the hallway on a bicycle, copy a number from a dial, and ride back to the main control room. This is the place where America's atomic energy starts.

How do we start the chain reaction?

Once you have enough of the right isotope, there is no trick at all to starting a chain reaction. You simply put enough of the isotope together in a lump and — off it goes!

How much is enough? It depends on the isotope. It depends on whether you are making a bomb or a furnace. It depends on how fast you let the neutrons travel. So you really have to calculate a different "enough" each time you use atomic energy. Some of these "enoughs" are still military secrets. This amount is called the *critical mass.* Because when you have it, you have a little crisis on your hands.

Why is there a "critical mass"?

If you have less than the critical mass, the neutrons that come shooting out of your first split nucleus may be wasted. Since atoms are mostly empty space, a neutron can go quite far, even through a heavy metal like uranium, before it bumps into a nucleus. And before it has a chance to do that, it might have shot right out of the lump. So if the lump is too small, so many neutrons are wasted that no chain reaction starts.

But if the lump is large enough, somewhere in it one of the billions and billions of atoms will split. It may split by itself, because uranium is radioactive. Or it may be split by one of the strange rays from outer space called *cosmic rays*. And when it splits, its neutrons will send the atomic blaze sweeping through the critical mass.

How does an A-bomb work?

The simplest kind of atomic chain reaction is the one that takes place in a bomb. In the bomb are two or more lumps of isotope. Each lump weighs less than the critical mass, but together they weigh more than the critical mass. They are a safe distance apart. But back of these lumps are small lumps of ordinary explosive. At the right moment, these explosives are set off. They shoot the isotope lumps toward each other. The critical mass is formed. The atom bomb goes off.

First there is one fission. Then the two neutrons cause two fissions. Then each causes two, so there are four. Eight. Sixteen. Sixty-four. . . .

It does not sound fast. But it is surprising how fast the numbers grow when you keep multiplying by two! In the tenth "generation" of fissions, there would be 512. In the twentieth — 524,288. In the eightieth — more than 1,208,900,000,000,000,000,000,000. And all this would happen in a fantastically small fraction of a second.

That is what happened at Hiroshima on August 6, 1945.

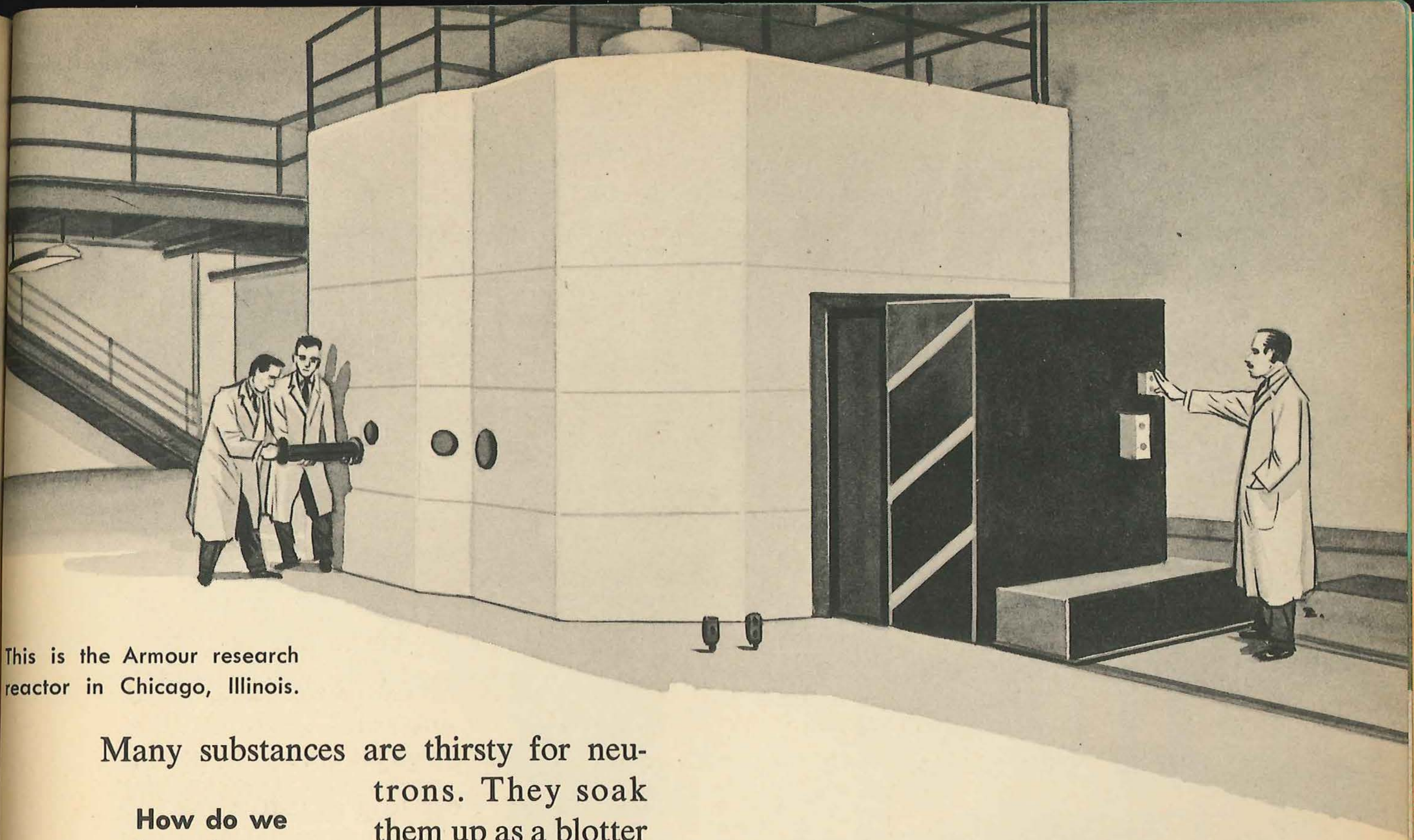
How can we tame the A-bomb?

If atomic energy could be used only for blowing up people, not many scientists would have worked on it. Even while the war was going on, physicists and engineers were busy inventing machines which would keep chain reaction going, but going slowly, so the energy could be used to run electric generators, ships, and perhaps even airplanes. These machines are called *reactors*.

Three of the hardest problems these scientists had to solve were: Getting enough neutrons. Not getting too many neutrons. Making the neutrons go at the right speed.

They got enough neutrons because the right isotopes had to be manufactured to use in the war.

They had to learn how to keep the chain reaction from building up with an explosion — 2, 4, 8 and *out!* It is one thing to drench your U-235 or plutonium with flying neutrons in a bomb you have dropped on your enemy. It is another thing to do it when you are anywhere around. In order to run a reactor, you have to have just the right number of neutrons — not too many, not too few. And you cannot learn to do this by trial and error, because you can only make *one* atomic error.



This is the Armour research reactor in Chicago, Illinois.

How do we keep from getting too many neutrons?

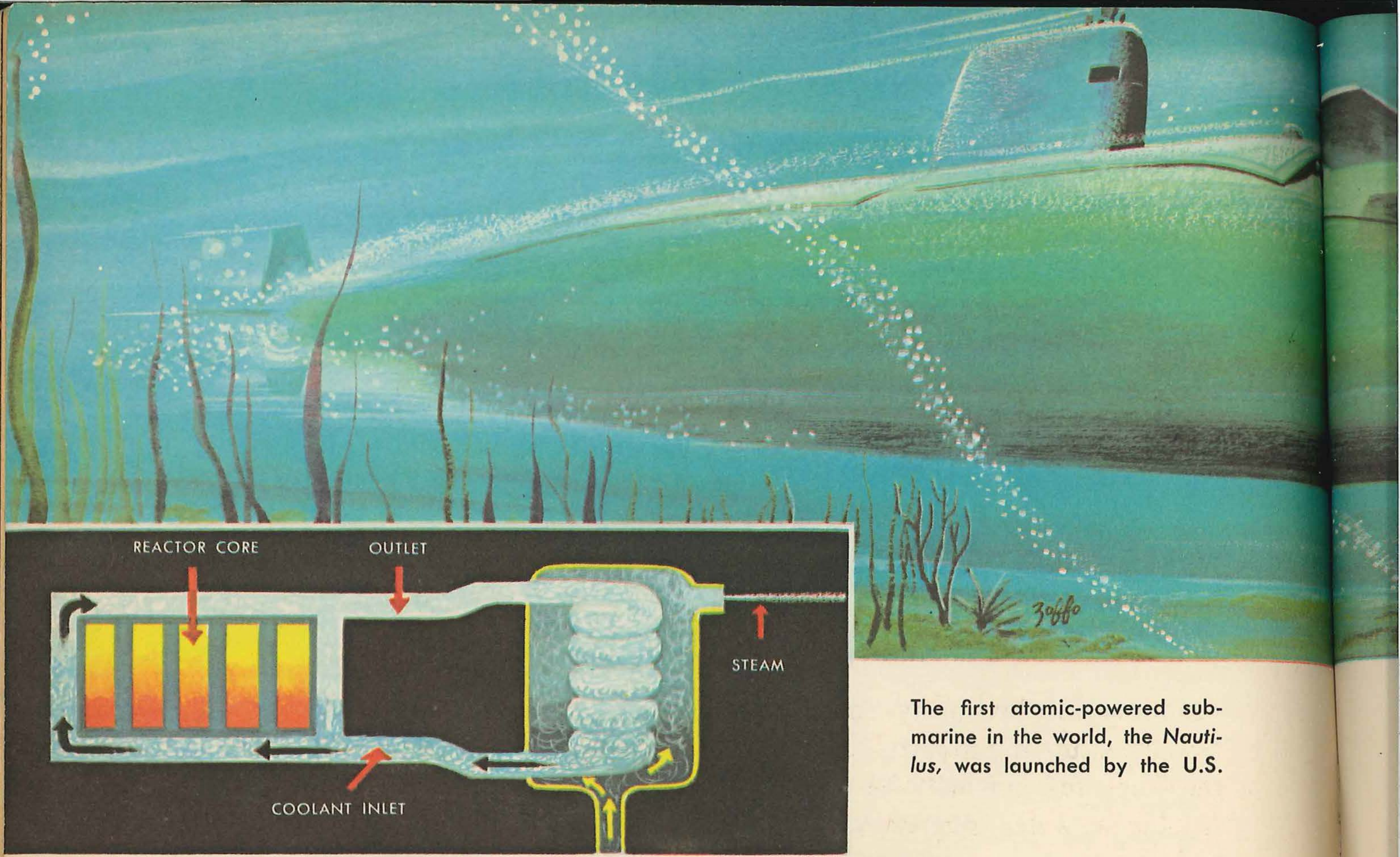
Many substances are thirsty for neutrons. They soak them up as a blotter soaks up water. This means that all the things with which you build a reactor must be very pure, so that you do not waste neutrons. But it also means that you can put safety-controls in your reactor. In Professor Fermi's first working reactor on the squash court at Stagg Field, he put rods of cadmium, a neutron-thirsty metal. A hasty movement of an inch too much in putting out a rod might have meant disaster. He had three men ready with pails of cadmium stuff just in case. Now we know a lot more about how reactors will react, and we have learned how to make them safe.

And the scientists learned to control the speed of neutrons. This was important because, for most of the reactors we have invented so far, slow-moving neutrons are better than fast-moving neutrons. That sounds strange.

Why are slow neutrons better than fast neutrons?

But suppose you are sitting with your family in a restaurant. You have been sitting there for twenty minutes and no one has taken your order or even brought the rolls, and you are all fidgety. Waiters are going past, carrying food to other tables. The whole family is trying to attract their attention. Two waiters pass. One is rushing along with a tray of empty dishes. The other has just made out somebody's bill and is walking slowly. Which do you think you can get to stop at your table?

And the problem is more complicated than that. Suppose someone at the next table was also trying to call a waiter. And suppose he was very good at it, especially at tripping up fast-moving waiters. The only waiter you would ever catch would be a slow waiter. Unless you have pure U-235 in your reactor,



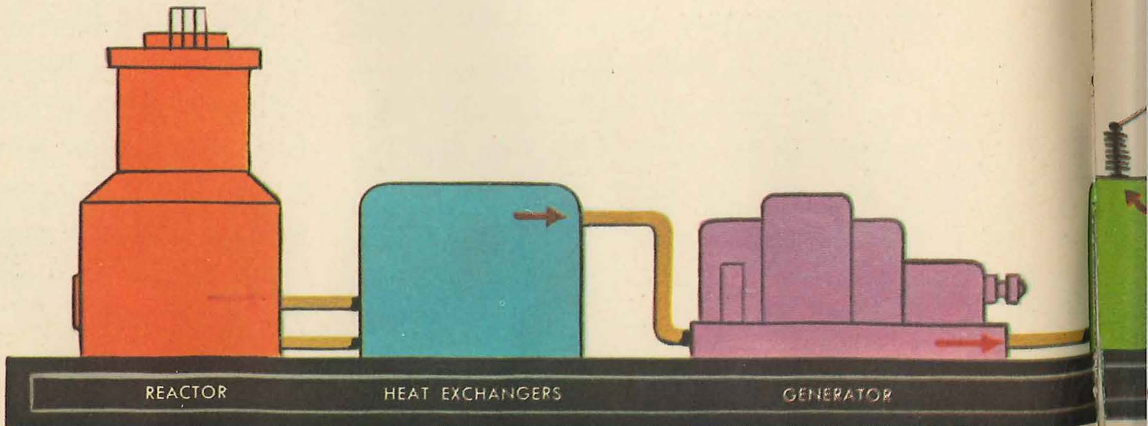
The first atomic-powered submarine in the world, the *Nautilus,* was launched by the U.S.

you must slow down your neutrons. Because if there is any U-238, it will grab the fast neutrons and not *split*. The only neutrons the U-235 could get would be the slow ones.

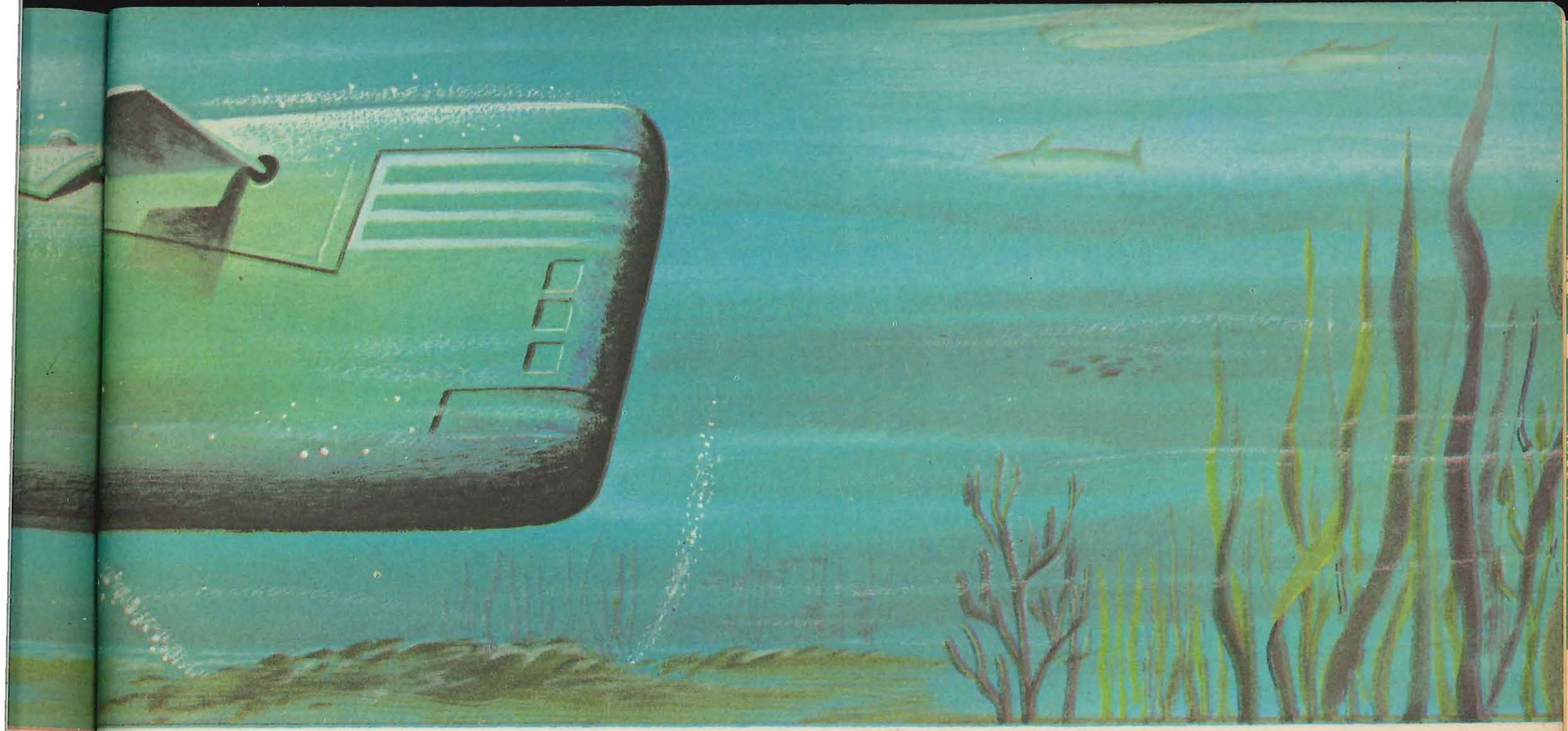
Many things slow down neutrons. But you have to pick things that will not absorb them. One of the first and best is carbon. Professor Fermi chose carbon, in the form of graphite, to put between the little lumps of uranium in the Stagg Field reactor.

How do we make the neutrons slow down?

Another slower-down of neutrons is water. Water is easy to handle, and it is especially useful because it boils. If the chain reaction starts to get out of hand and the reactor gets too hot,

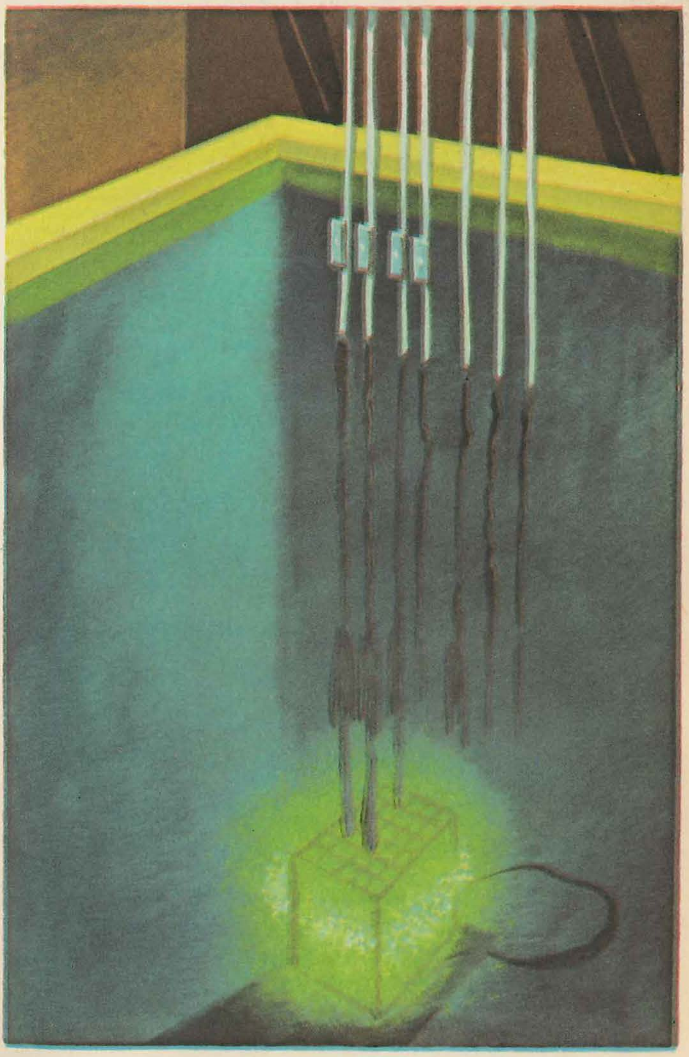


Atomic energy has been transformed into electricity, supplying power to communities.

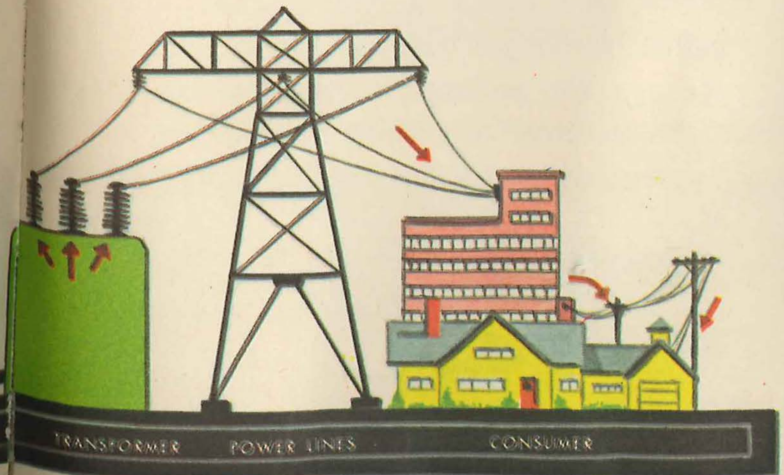


the water will boil away, the neutrons will speed up and miss the nuclei, and the chain reaction will die down. The trouble is, water is made of hydrogen and oxygen atoms, and ordinary hydrogen is very greedy for neutrons. *Heavy hydrogen,* the second isotope, is not; and *heavy water,* made with this isotope, is used a lot as a moderator. But it is rare and expensive, so we have been learning how to use ordinary water.

A substance used to slow down neutrons is called a *moderator*. The first thing to do in designing a reactor is to choose the moderator. We talk about



In an atomic "swimming pool" reactor, moderated by water, the nuclear radiation causes a blue glow.



reactors as being *water moderated*, *graphite moderated* and so on.

What kinds of reactors can we build?

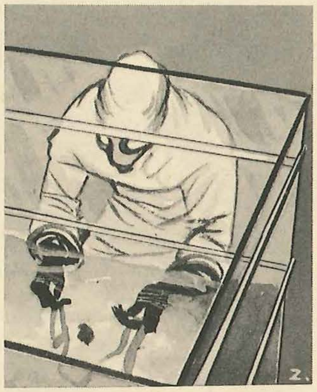
Engineers and physicists have now invented dozens of different kinds of reactors to do different things. The kind of reactor that has the atomic fuel buried in a stack of graphite is called an *atomic pile*. The kind that keeps the fuel down in a tank of water is called a *swimming pool reactor*. In some reactors, melted metal is flushed through the atomic furnace to carry off the heat to boil water and run a steam turbine. In some, the water for the steam is passed right through the heat of the furnace. Some use plutonium. Others use various mixtures of U-238 and U-235.

Reactors can do two things. They can make something hot. And they can bombard something with various flying particles.

How can we use reactors?

Power reactors are furnaces. They heat water or some other stuff that boils, and drive engines. We have a whole fleet of submarines whose engines are run by atomic heat. It is a wonderful way to run a submarine, because it does not use up air and because a few rods of nuclear fuel will last for a long time. So the sub can run for months under water without coming to the surface to get air or fuel.

Power reactors also run huge electric generating stations. We are having a little trouble making them run airplanes or cars, because a reactor has to be rather heavy. This is because it must be covered with thick metal *shielding*, so that particles and rays do not escape and burn or poison people.



Atomic researchers must "shield" themselves from radiation. They handle "hot" materials only with instruments or with special gloves.

Why do we need new elements?

Reactors are often used to change elements into other elements. Sometimes this is done to make fuels like plutonium. (A very important reactor is the *breeder reactor*, which not only makes power but also cooks up atomic fuels like plutonium at the same time.) But often it is to turn ordinary elements into artificial isotopes that are radioactive. These are tremendously important, especially in medicine. Suppose you are a doctor who wants to find out what is happening in some part of a patient's body. You can tack a "label" on a certain chemical by making it a little radioactive, and follow it with a detector called a *Geiger counter* as it goes through the patient. Radioactive isotopes are used for treating diseases like cancer that used to be very hard to get at.

Every day, new uses are found for reactors. We are just beginning to live in the Atomic Age.

Suns Made to Order

Where do stars get their energy?

Even if you had a good rocket, you could not travel to the sun and take a sample of it, because you would burn to a crisp long before you got there. So all that anyone can do to find out what makes the sun hot is to study atomic physics and try to match its facts with the facts astronomers have learned by watching the sun from our cool little planet 93,000,000 miles away.

But we think that the sun — like all the stars — makes nuclear energy. It does not make it by fission, but by *fusion.* It takes atoms of hydrogen, which are very simple atoms with one proton in the nucleus, and it crushes them together so that they turn into helium, which has two protons in the nucleus. Our binding energy chart tells us that an enormous amount of mass — atomically speaking — is converted into energy when this happens.

Now we have a lot more questions than answers about this.

What happens inside the sun?

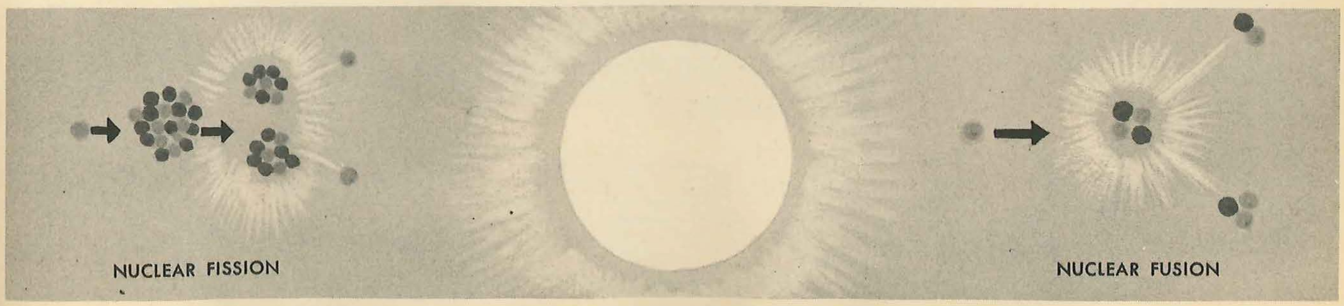
How does the sun squeeze these atoms? It is so big that its gravity, pulling everything toward the center of its huge mass, creates an unbelievable pressure there. The matter at the sun's center is stripped-down hydrogen — or rather, squashed-flat hydrogen — just nuclei, because there is no room for the outer electrons. The inside of the sun is also hot — about 20 million degrees centigrade. Under these conditions, protons turn to neutrons, shoving out electrons. Proton-neutron pairs — which are the nuclei of heavy hydrogen — are forced together to become helium. This probably happens in many ways, but all of them give off energy.

It takes a little over eight minutes for that energy to travel to the earth once it works its way to the surface of the sun. But it takes 10,000 years for the energy to work its way from the center of the sun to the surface.

How does an H-bomb work?

When the trial atom bomb exploded at Alamogordo on July 16, 1945, scientists realized that they could not only make fission-energy, they could now make fusion-energy the way the sun does. For at the heart of Fat Man, there were millions of degrees of temperature, just as there are at the heart of the sun. And there were millions of pounds of pressure. If we were

Fission: When an atomic nucleus splits. *Fusion:* Two lightweight atomic nuclei join, forming a heavier nucleus.



to put the right kind of hydrogen atoms into the heart of an atomic explosion, we could make a second explosion of energy that would make Fat Man look scrawny.

The right kind of hydrogen is the heaviest of the three hydrogen isotopes, tritium, a radioactive atom with one proton and two neutrons in its nucleus. By crushing a tritium nucleus with another tritium nucleus, we get helium and two neutrons and 11 million electron volts. By crushing a tritium nucleus into a "heavy hydrogen" nucleus, we get helium, one neutron, and 17 million electron volts.

Although the H-bomb that exploded on Eniwetok Atoll in the Pacific on November 1, 1952 — and not only melted a whole island but boiled it away — is hidden in military secrecy, we know now that *there is no limit to the energy we can make from the atom.*

Can we tame the H-bomb?

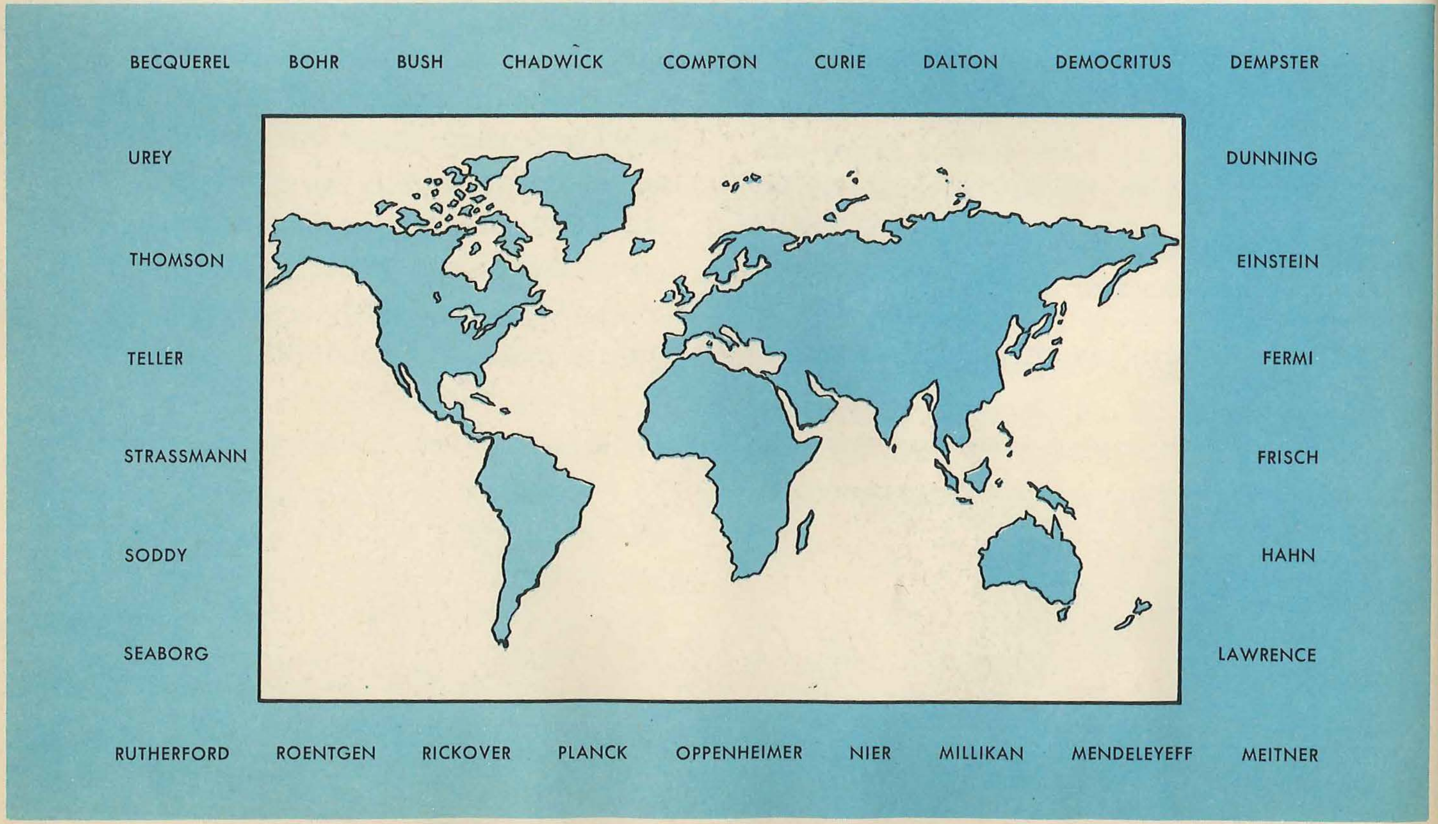
The trouble is, we have found no way to control this terrible and wonderful new force. We can make the pressures and temperatures we need — for an instant. But if we want to make fusion energy steadily, as the sun does, we must have a bottle that will hold those pressures and those temperatures. What can hold them?

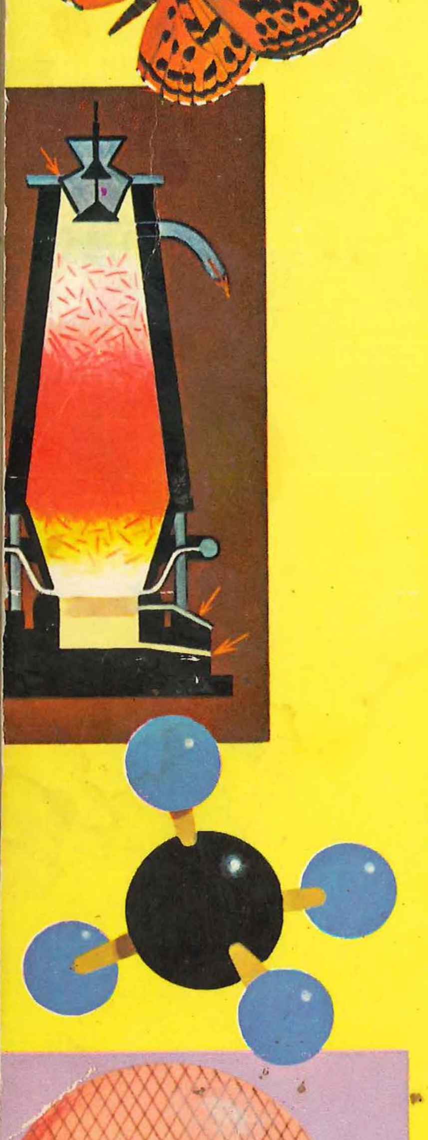
We have tried strange magnetic bottles, in which gases are trapped and squeezed without ever touching solid matter. But they have not worked.

We are learning to set off H-bombs underground, and slowly draw off the heat.

But we have only begun. At this moment, in some laboratory somewhere in the world, someone may be watching queer streaks on a screen or the needle on a dial that says another, even greater, Atomic Age is about to begin.

Below are some of the scientists who have contributed to our understanding and development of the Atomic Age.





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